Document Number: AFT-2008-000155, Rev. 001(0) PSNE Control Number: PSN-2009-0117

4S Seismic Base Isolation Design Description

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February 2009

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LIST OF ACRONYMS AND ABBREVIATIONS

4S	Super-Safe, Small and Simple
ALMR	advanced liquid metal reactor
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
CRIEPI	Central Research Institute of Electric Power Industry
DA	Design Approval
DOE	Department of Energy
FPS	friction pendulum system
HDR	high-damping rubber
IBC	International Building Code
IHX	intermediate heat exchanger
JEAG	Japan Electric Association Guide
JSME	Japan Society of Mechanical Engineers
LRB	lead-rubber bearing
MCE	maximum considered earthquake
NRC	Nuclear Regulatory Commission
R&D	research and development
SAFR	Sodium Advanced Fast Reactor
SBI	seismic base isolation
SEI	Structural Engineering Institute
SMiRT	Structural Mechanics in Reactor Technology
SRP	Standard Review Plan
SSE	safe shutdown earthquake

1 SCOPE

This report describes the seismic base isolation (SBI) design of the 4S reactor building for U.S. Nuclear Regulatory Commission (NRC) review as part of the pre-application process toward eventual Design Approval (DA). In the expectation that 4S will be constructed in the U.S., the design is intended to meet codes and regulations in the U.S. Currently, there are no codes and regulations specifically for the application of seismic base isolation to nuclear power plants in the U.S. Therefore, the present 4S seismic base isolation design is based not only on existing U.S. codes and regulations, but also on a Japanese guideline for the application of seismic base isolation to nuclear power plants.

2 INTRODUCTION AND BACKGROUND

Seismic base isolation is a building protection technique that reduces the seismic force input to a structure by the installation of isolation devices, generally between the building and its supporting base. Usually, such isolation devices are composed of multiple alternating layers of steel plates and rubber.

This section provides a brief introduction to seismic base isolation and the related codes, standards, and guidelines.

2.1 Application of SBI to General Buildings

A general discussion of the development and application of SBI was presented by Dr. I. D. Aiken in an article for Response Control and Seismic Isolation of Buildings, edited by Okamoto and Higashino, 2006.(2.1-1)

According to this article, construction of the first seismically isolated building in the U.S. was completed in 1985, and by mid-2005 there were approximately 80 seismically isolated buildings in the U.S.

The number of applications of SBI in Japan was summarized by the Japan Society of Seismic Isolation in an article in the magazine *MENSHIN*, No. 61, August 2008.(2.1-2) The article states that the number of buildings with SBI increased dramatically in 1995, when the Great Hanshin-Awaji Earthquake struck, causing tremendous damage. Since then, about 100 to 200 SBI buildings have been constructed every year. Between 1982 and 2006, a total of almost 2000 SBI buildings were constructed in Japan. That number includes high-rise buildings (buildings 60 meters or more in height). According to a data sheet in the magazine, 103 high-rise buildings with SBI were constructed between the years 2000 and 2007. In addition to the approximately 2000 base-isolated buildings, 2530 individual family houses have been constructed with SBI.

2.1.1 Base Isolation Devices

Some of the most widely used types of base isolation devices are described below.

2.1.1.1 Lead-Rubber Bearings (LRB)

An LRB device is composed of layers of steel plates and natural rubber layers, which provide low stiffness in the horizontal direction, and one or more lead plug elements inside, which provide a damping effect. Lead-rubber bearings were used for the first U.S. building retrofit isolation project (1987-88), as well as the first U.S. bridge isolation project (1984), also a retrofit. LRBs have been used for about 40 buildings since that time in the U.S.

2.1.1.2 High-Damping Rubber (HDR) Bearings

An HDR device looks like an LBR device, but has no lead plug element inside, because the rubber itself has a sufficient damping effect. HDR bearings were first used for seismic isolation in the U.S. in the Foothill Communities Law & Justice Center, constructed in 1985-86. HDR bearings have been used in about 20 buildings since then in the U.S.

2.1.1.3 Friction Pendulum System (FPS)

FPS bearings were developed in the U.S. in the late 1980s. The original FPS bearing configuration consisted of a single spherical dish within which slid a spherical articulated slider. The low stiffness of the system was achieved by the curvature radius of the spherical dish, and damping provided by friction on the sliding interface. Subsequent configurations have included two opposed spherical dishes (which allows for a more compact bearing), a bearing that is capable of resisting tension, and recently, a bearing made up of three different sliding radii (called the triple pendulum bearing).

2.1.1.4 Hybrid Systems

Most U.S. building isolation projects have utilized a single type of bearing for the isolation system. This approach is in contrast to isolation systems in Japan, where it is more common to use combinations of several types of devices in one system. Even so, there are a number of systems in the U.S. that use several components These have included:

- LRBs or HDR bearings plus flat sliding bearings (usually used to support lower loads)
- HDR bearings plus viscous dampers
- FPS bearings plus viscous dampers
- HDR bearings plus flat sliding bearings plus viscous dampers
- Natural rubber bearings plus viscous dampers

The flat sliding bearings have included PTFE-stainless sliding interfaces with either a laminated rubber backing or a pot bearing to provide rotational flexibility.

Viscous dampers have been the only type of damping device used in the U.S. for isolation systems. Unlike in Japan, where various types of yielding steel devices are commonly used for isolation systems, these have not been used in the U.S.

2.1.2 Application of SBI to Nuclear Reactor Buildings

Tajirian[2.1-3] and others have described the application of SBI to nuclear reactor buildings in France, South Africa, Mexico, and the United States. In France, a design supported on 1800 neoprene pads was developed for the four-unit Cruas plant on a site with moderate seismicity where the safe shutdown earthquake (SSE) acceleration is 0.2g.[2.1-4] A two-unit plant in Koeberg, South Africa (SSE acceleration 0.3g) uses a design supported on 200 pads, with sliding plates that limit shear strain in the pads to the same level as at moderate sites.[2.1-5]

In the United States, the Department of Energy (DOE) sponsored a design project to support the development of a standard seismic isolation design. In this project, an advanced liquid metal reactor (ALMR) is supported on 66 high-damping rubber bearings, for sites with maximum SSE horizontal and vertical accelerations of 0.5g.[2.1-6] A large number of seismic isolation and full- and reduced-scale bearing tests were performed.[2.1-7, 2.1-8]

The DOE-sponsored Sodium Advanced Fast Reactor (SAFR) project is unique for providing both horizontal and vertical isolation by using bearings with thicker rubber layers than usual. The building is supported on 100 seismic isolators and designed for a horizontal frequency of 0.5 Hz and a vertical frequency of 3 Hz. A large number of reduced-scale bearing tests were performed.[2.1-9]

2.2 Codes, Standards, and Guidelines

Codes, standards, and guidelines that the 4S seismic design conforms to are discussed in this section.

2.2.1 ASCE 7-05, Minimum Design Loads for Buildings and Other Structures

The American Society of Civil Engineers (ASCE) ASCE 7-05, Chapter 17, "Seismic Design Requirements for Seismically Isolated Structures," states that every seismically isolated structure and every portion thereof must be designed and constructed in accordance with the requirements therein. This document defines the loading, design properties, and testing requirements for isolated structures and isolation systems. It is cited in several codes, including IBC 2007. The key sections of Chapter 17 are as follows:

- Section 17.3, Ground Motion for Isolated Structures

  Covers response spectrum properties and ground motion selection and scaling requirements.

- Section 17.4, Analysis Procedure

  Defines which types of structures can use response spectrum design methods (equivalent lateral force procedure) and which must use time-history analysis.

- Section 17.6, Dynamic Analysis Procedures

  Defines dynamic analysis procedures for isolated structures.

- Section 17.7, Design Review

  Describes the requirement that all isolation systems and related test programs be reviewed by an independent engineering firm.

- Section 17.8, Testing

  Describes prototype test requirements and acceptance criteria required for all projects.

2.2.2 ASCE/SEI Standard 43-05, Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities

This standard was published by ASCE in 2005. It provides seismic design criteria that are more stringent than normal building codes with the goal of ensuring that nuclear facilities can withstand the effects of earthquake ground shaking with desired performance goals.

A report by Brookhaven National Laboratory, NUREG/CR-6926 BNL-NUREG-77569-2007, "Evaluation of the Seismic Design Criteria in ASCE/SEI Standard 43-05 for Application to Nuclear Power Plants," describes the results of the review and evaluation of ASCE/SEI Standard 43-05 to determine the applicability of this standard to the seismic design of nuclear power plants. This report reviews the standard, its references, and other supporting documents.

2.2.3 NUREG-0800, Standard Review Plan for the Review of Safety Analysis Report for Nuclear Power Plants (Rev. 3, 03/2007)

The Standard Review Plan (SRP) provides guidance to NRC staff in performing safety reviews. Chapter 3, "Design of Structures, Components, Equipment, and Systems," covers issues related to structural design and loading. Section 3.7.1 covers seismic design parameters.

2.2.4 NRC Regulatory Guides

Regulatory Guides to which the 4S seismic design conforms include the following:

- RG 1.29 Seismic Design Classification (Rev. 4, ML070310052, 03/2007)
- RG 1.60 Design Response Spectra of Nuclear Power Reactors (Rev. 1, ML003740207, 12/1973)

  Description and commentary related to RG 1.60 can be found in NUREG/CR-6926 (pp. 9-10).
- RG 1.61 Damping Values for Seismic Design of Nuclear Power Plants (Rev. 1, ML070260029, 03/2007)
- RG 1.92 Combining Modal Responses and Spatial Components in Seismic Response Analysis (Rev. 2, ML053250475, 07/2006)
- RG1.122 Development of Floor Design Response Spectra for Seismic Design of Floor-supported Equipment or Components (Rev. 1, ML003739367, 02/1978)

The following Regulatory Guides for site-specific evaluation are regarded as references for the current 4S standard design.

- RG 1.165 Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion (Draft DG-1015 issued 11/1992, Draft DG-1032 issued 02/1995)

  Commentary related to RG 1.165 can be found in NUREG/CR-6926 (pp. 9-11).

- RG 1.208 A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion (Rev. 0, ML070310619, 03/2007)

2.2.5 JEAG 4614-2000 (Japanese Guideline)

The Japan Electric Association published "Technical Guidelines on Seismic Base Isolated System for Structural Safety and Design of Nuclear Power Plants (JEAG 4614-2000)[2.1-10] in 2000. This document is based on the results of a 10-year research and development (R&D) program sponsored by the Japanese government. The guideline was developed for fast breeder plants, but has since been revised to cover light water reactors as well.

The results of the development program have been published in many papers. The papers appear in the references of the JEAG guideline. Many of the papers have been presented in English at meetings of the World Conference on Earthquake Engineering and the International Conference on Structural Mechanics in Reactor Technology. [2.1-11 to 2.1-25]

2.3 References

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2.1-3 Tajirian, F. F., "Base Isolation Design for Civil Components and Civil Structures," Proceedings, Structural Engineers World Congress, July 1998.

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2.1-5 Jolivet, J., and M. H. Richli, , "A seismic foundation system for nuclear power stations," 4th International Conference on Structural Mechanics in Reactor Technology, 1997.

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2.1-9 Aiken, I. D., J. M. Kelly, and F. F. Tajirian, "Mechanics of low shape factor elastomeric seismic isolation bearing," Report No. UCB/EERC-89/13, University of California, Berkeley, 1989.

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2.1-13 Ishida, K., et al., "Shaking table test on base-isolated FBR plant model Part 1, Part 2," 11th International Conference on Structural Mechanics in Reactor Technology, 1991.

2.1-14 Sonoda, Y., et al., "Feasibility study on the seismic isolation of pool type LMFBR," 9th International Conference on Structural Mechanics in Reactor Technology, 1987.

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2.1-17 Ishida, K., H. Shiojiri, et al., "Elastic-plastic analysis of base concrete for base-isolated FBR," 11th International Conference on Structural Mechanics in Reactor Technology, 1991.

2.1-18 Ishida, K., et al., "A study on analytical methods to evaluate sloshing phenomena of base-isolated LMFBR," 11th International Conference on Structural Mechanics in Reactor Technology, 1991.

2.1-19 Mazda, T., K. Ishida, et al., "A study on the design method of the laminated rubber bearings for FBR," Proceedings of ASME Pressure Vessels and Piping Division Conference, 1994.

2.1-20 Ohtori, Y., T. Mazda, et al., "Dynamic characteristics of lead rubber bearings with dynamic two-dimensional test equipment," Proceedings of ASME Pressure Vessels and Piping Division Conference, 1994.

2.1-21 Fujita, T., Ishida, K., et al., "Study for the prediction of the long-term durability of seismic isolators," *Rubber World*, Vol. 211, No. 3, December 1994.

2.1-22 Fujita, T., T. Mazda, et al., "Study for the prediction of the long-term durability of seismic isolators – Part 1, Part 2," The International Rubber Exposition and Educational Conference, 144th fall international technical meeting of the ACS Rubber Division, Paper No. 95, October 1993.

2.1-23 Watanabe, Y., G. Yoneda, et al., "Investigation of Aging Effect for Laminated Rubber Bearings of Pelham Bridge," 11th World Conference on Earthquake Engineering, June 1991.

2.1-24 Amada, K., et al., "Experimental and analytical study on cross-over piping system in seismic isolation FBR plant (I) MAIN STEAM PIPING," 12th International Conference on Structural Mechanics in Reactor Technology, K19/6, 1993.

2.1-25 Amada, K., et al., "Experimental and analytical study on cross-over piping system in seismic isolation FBR plant (II) CCWS-SEA WATER PIPING," 12th International Conference on Structural Mechanics in Reactor Technology, K19/7, 1993.

3 BASE ISOLATION DESIGN

3.1 Basic Configuration

3.1.1 Reactor Building

Figures 3.1-1 and 3.1-2 show a representative plan and vertical section of the 4S reactor building. Fundamental information on size and weight is given in Table 3.1-1.

Base isolation is provided at the bottom of the reactor building, and the isolators are set on a base mat on the ground. The outside of the reactor and reactor building is surrounded and secured by soil retaining walls with a seismic gap of sufficient size. The gap size is described in Section 3.7.2 based on analytical results.

3.1.2 Isolators

Some types of isolators were described in Section 2.1.1. According to the Japanese guideline JEAG 4614-2000, isolators are limited to the following three types, which are fundamentally similar to those tested during the development of the guideline.

- Lead-rubber bearings (LRBs)
- Natural rubber bearings plus separate dampers
- High-damping rubber (HDR) bearings

The "natural rubber plus separate dampers" type was not mentioned in Section 2.1.1, but is basically the same as the LRB type, since LRBs are composed of natural rubber bearings and lead dampers.

The current 4S design uses LRBs, but the other two types could also be used in the 4S design. Figure 3.1-3 shows a typical LRB configuration.

3.1.3 Dynamic Properties of Isolators

An LRB device is composed of natural rubber and a lead plug damper. Natural rubber is elastic, and the lead plug damper becomes plastic at low stress levels. Thus, as a whole, an LRB device has very nonlinear dynamic properties. Figure 3.1-4 shows a model of LRB dynamic properties that is used in the dynamic analyses.

The following parameters are essential.

3.1.3.1 Stiffness of Isolators

Stiffness of the isolators after yielding of the dampers is a key performance indicator of the isolator. Often, the stiffness is represented by the following natural period of vibration, T_2.

$$T_2 = 2\pi\sqrt{\frac{W}{k_2 \cdot g}}$$

where,

T_2: natural period of vibration defined by k_2
k_2: tangential stiffness after yielding of dampers
W: weight of the isolated building
g: gravitational acceleration

Figure 3.1-5 compares floor response spectra of two example cases, $T_2 = 2.0$ sec and $T_2 = 3.0$ sec. The floor response spectra represent the acceleration of the isolated base mat that supports the reactor. The other conditions used in the analyses are described later. For comparison, Figure 3.1-5 also shows the floor response spectrum of the nonisolated case. It is clear that the use of base isolation significantly reduces response acceleration at frequencies higher than 1.0 Hz. Table 3.1-2 shows the maximum relative displacement at the isolation level of the two cases.

As shown in Figure 3.1-5, softer isolation provides lower response acceleration. As for displacement, in general, softer isolation provides larger displacement, though the trend is not clear in Table 3.1-2. Less relative displacement between isolated and nonisolated portions of the building is better for the design of main steam pipes that travel across the seismic gap. Therefore, for the 4S standard design, it was decided to adopt the stiffer case, $\boldsymbol{T_2 = 2.0}$.

3.1.3.2 Yielding Force of Lead Plug Dampers

The yielding force of the lead plug dampers, Q_y, is given by the following equation:

$$Q_y = \beta W$$

where,

Q_y: horizontal shear force when dampers yield
W: weight of the isolated building

Figure 3.1-6 compares floor response spectra of two example cases, $\beta = 0.05$ and $\beta = 0.1$.

Essentially, larger values of β provide more damping, but increase response acceleration in the isolated building before the dampers yield.

The 4S standard design adopts the case of less yielding force of the lead plug dampers, $\boldsymbol{\beta = 0.05}$.

Table 3.1-1 Size and Weight of the Reactor Building	
Plan size	Approx. 30m x 24m
Depth from ground surface	Approx. 20m
Weight of isolated building including all mechanical components	14,126 tons

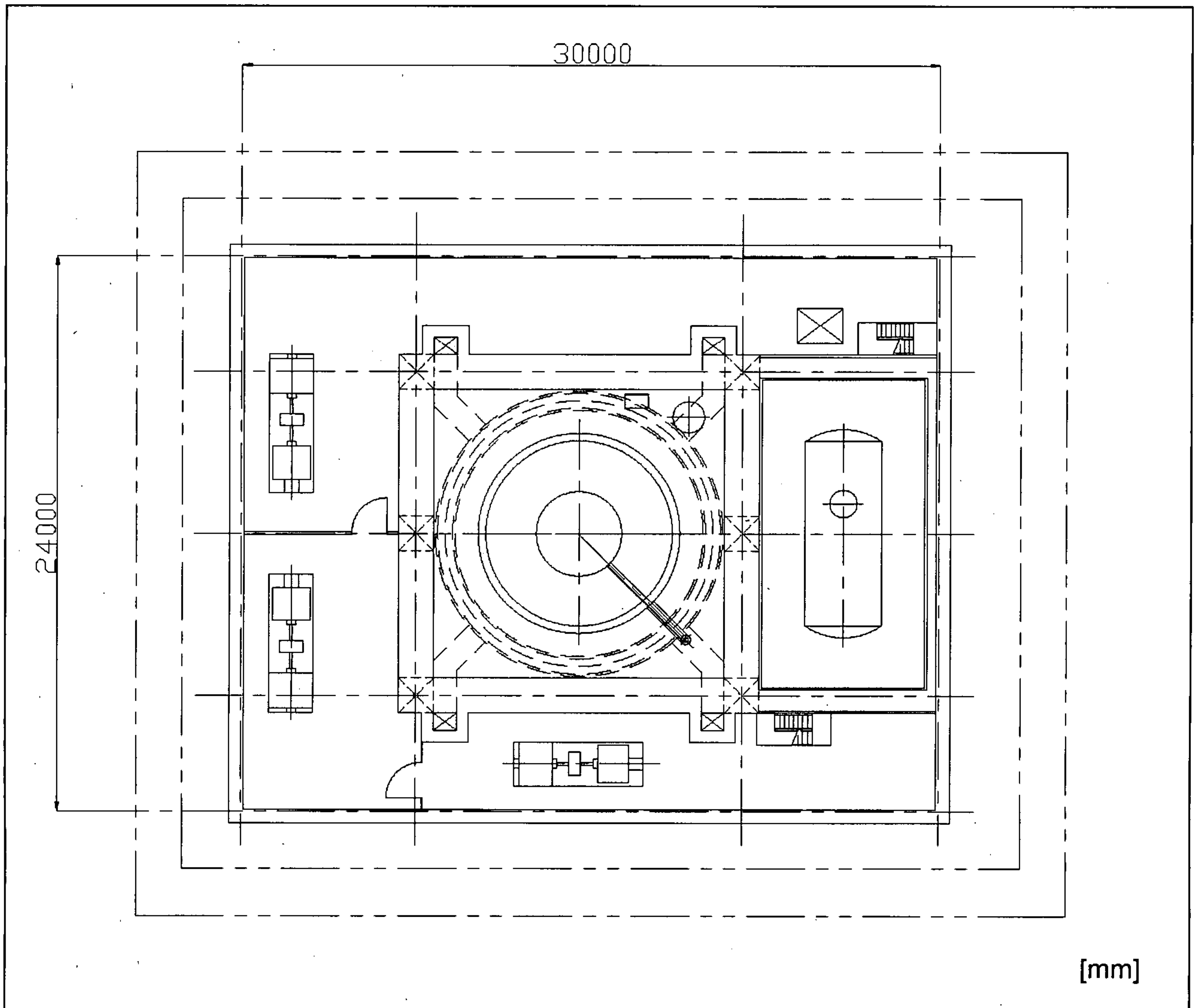


Figure 3.1-1 Plan of Reactor Building Basement Floor

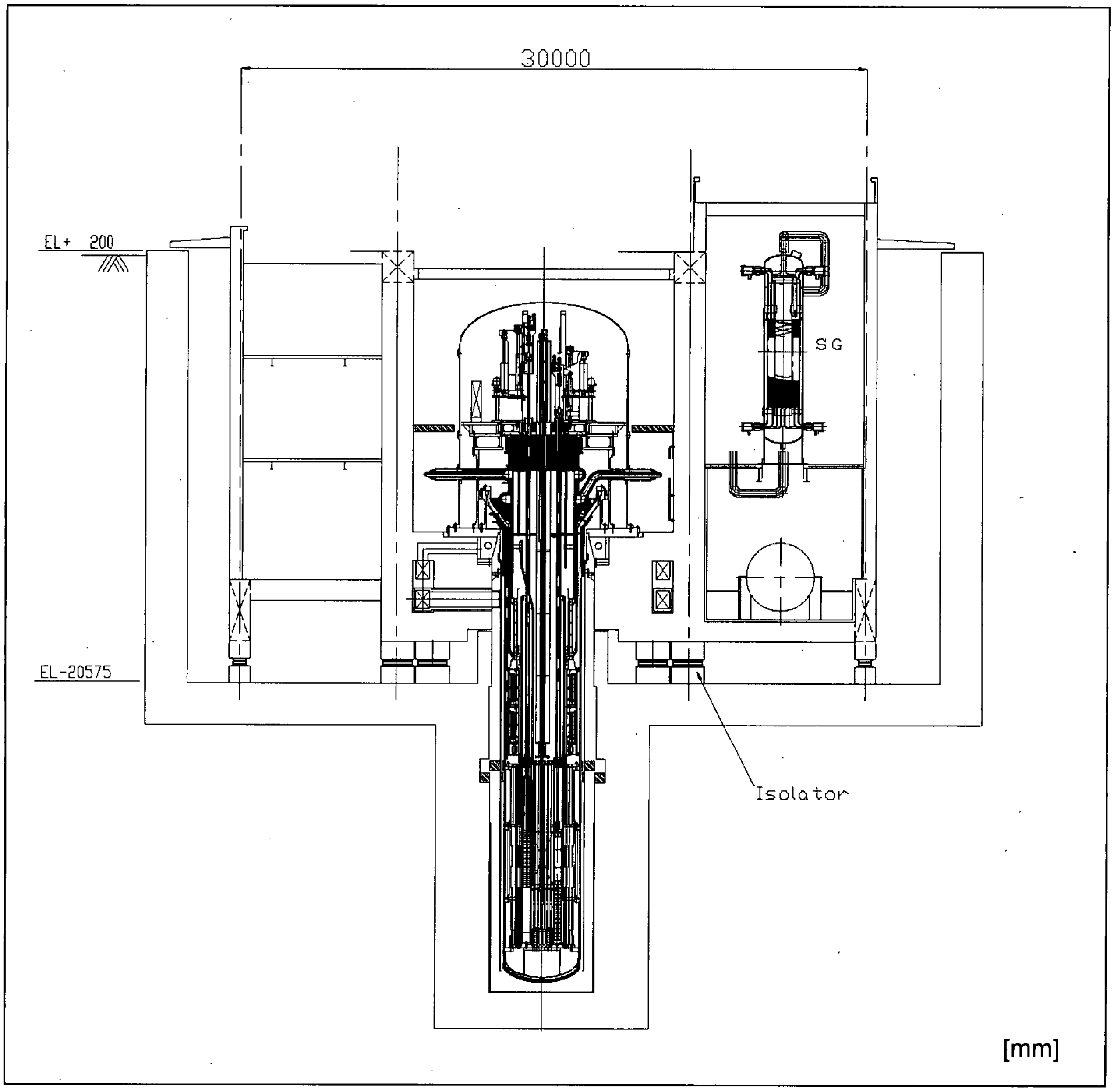


Figure 3.1-2 Vertical Section of Reactor Building

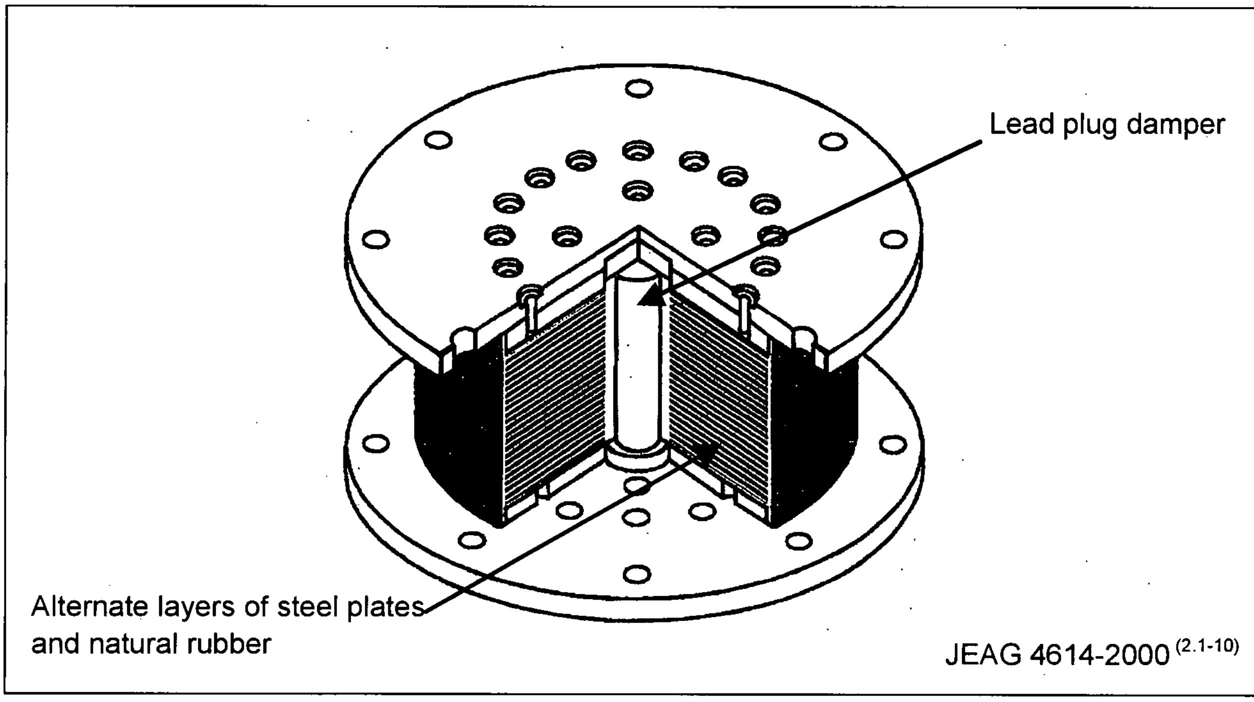


Figure 3.1-3 Lead-rubber Bearing (LRB)

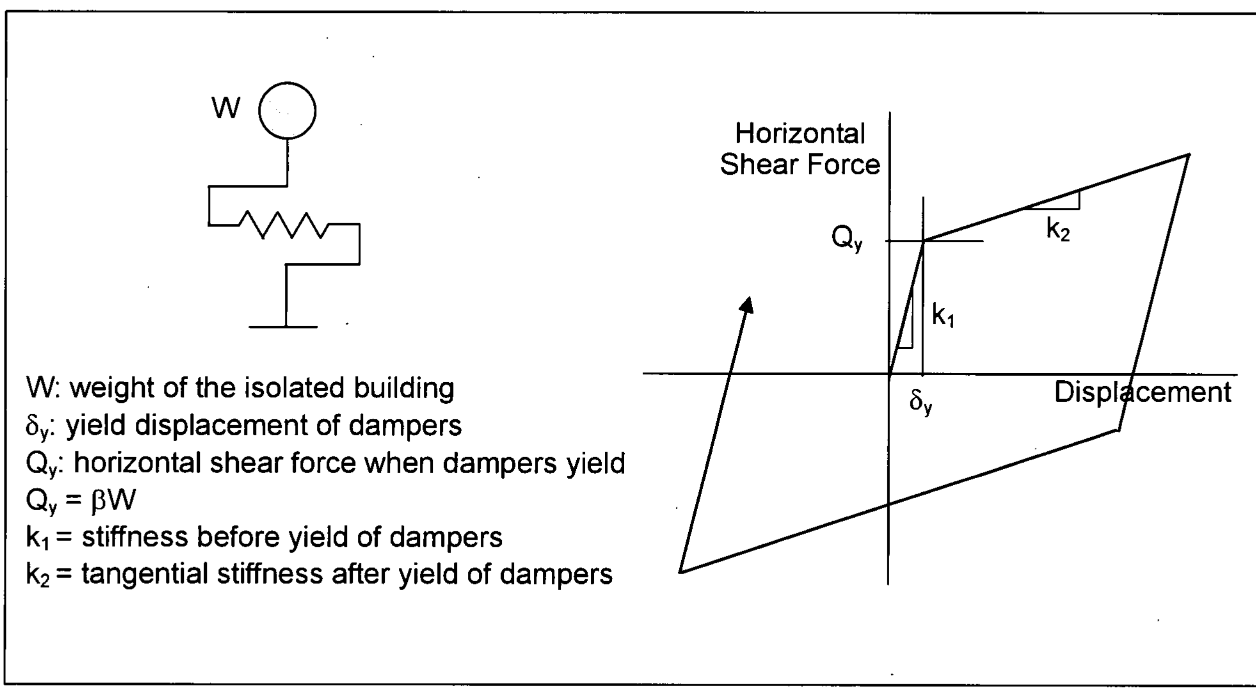


Figure 3.1-4 Model of LRB Dynamic Properties

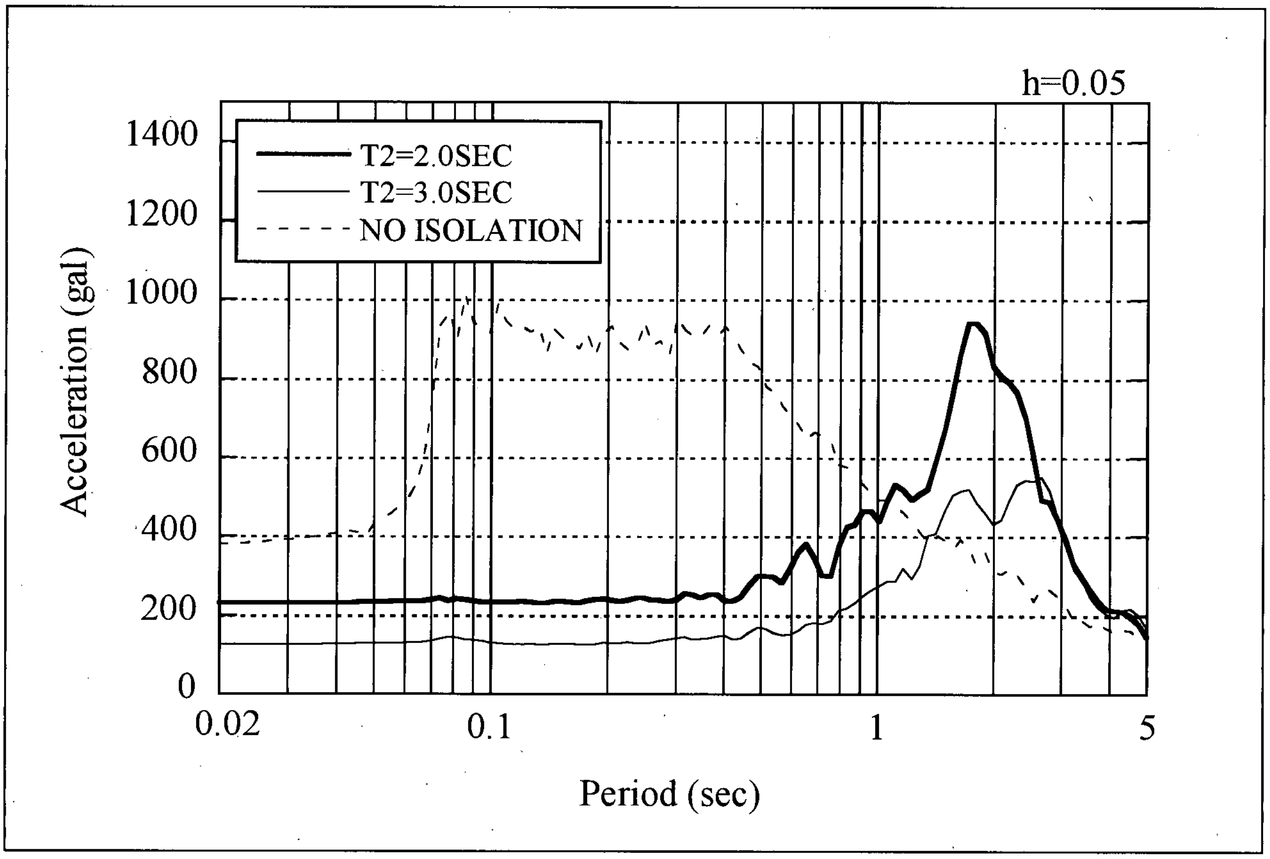


Figure 3.1-5 Floor Response Spectra of Isolated Base Mat

Table 3.1-2 Maximum Relative Displacement at Isolation Level	
Period of vibration T_2 (sec)	**Relative Displacement (mm)**
2.0	212
3.0	214

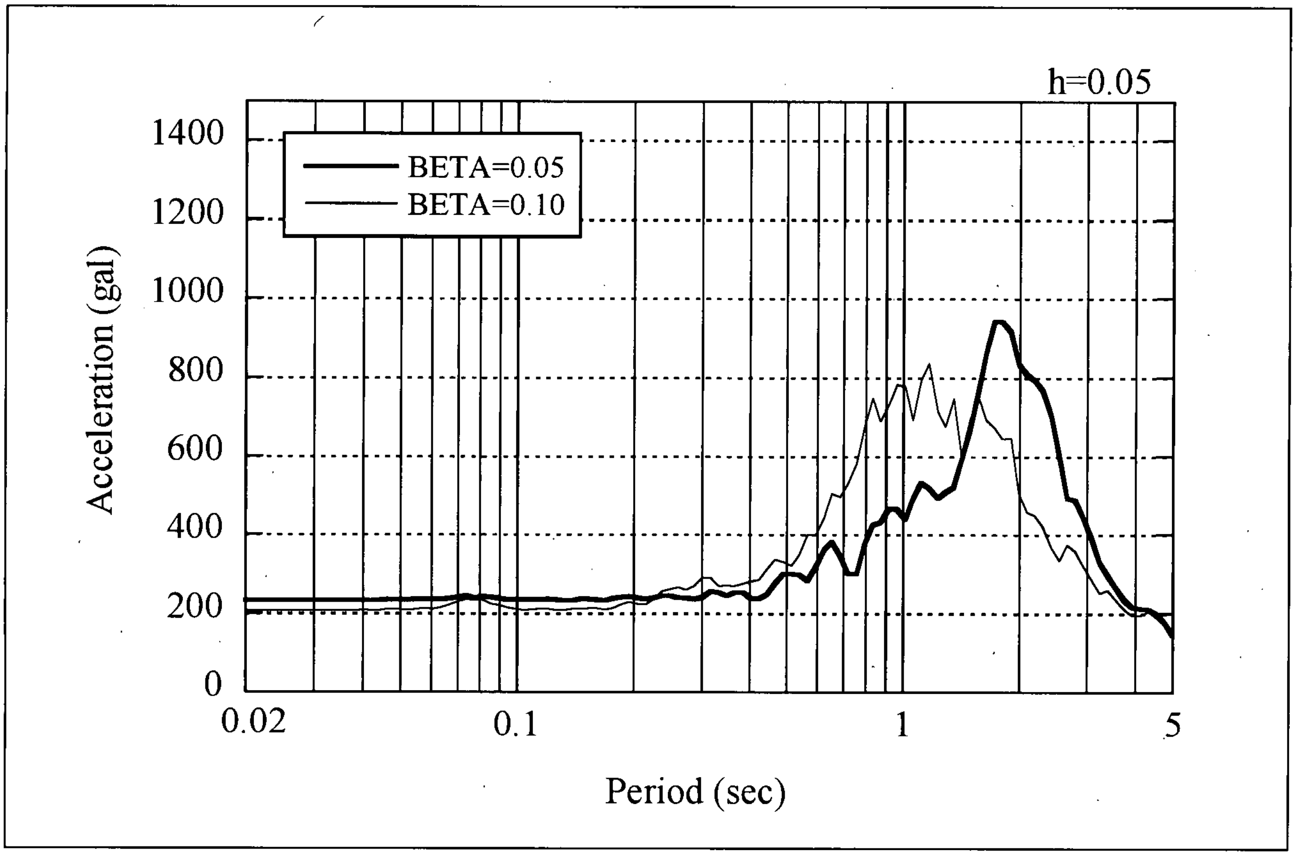


Figure 3.1-6 Floor Response Spectra of Isolated Base Mat

3.2 Analysis Model

Currently, dynamic response analysis is carried out independently for the horizontal and vertical directions. The amount of interaction between the horizontal and vertical directions is normally small, because the dynamic properties of isolated buildings in the horizontal direction are very different from those in the vertical direction.

Analysis software for nuclear plant seismic design must address soil-structure interaction. One set of programs that does this is SASSI 2000 [3.2-1], developed at the University of California, Berkeley and widely used in the U.S. It is intended primarily for linear analyses. However, analysis of base-isolated buildings in the horizontal direction must address both the nonlinearity of isolators and soil-structure interaction. Therefore, DAC3N, developed by Shimizu Corporation in Japan, is also used.

Analysis models are discussed in the following sections.

3.2.1 Isolated Reactor Building

The analytical model of an isolated building is a lumped mass and beam element model.

Figure 3.2-1 shows dynamic analysis models for the horizontal and vertical directions. Tables 3.2-1 and 3.2-2 list their parameters.

The civil structural portion of the three-story building in the ground is represented by nodes numbered 1, 2, and 3, which make up a concrete-filled steel structure. The isolated base mat is represented by node 4, and the base mat of the isolators on the ground is represented by node 5.

The reactor portion of the model is composed of the intermediate heat exchanger (IHX), shield plug, and reactor vessel, which are all supported on the isolated base mat of the building.

The damping value of the concrete-filled steel structure is 5.0 percent for the seismic intensity level of an SSE.

3.2.2 Seismic Isolators

A model of the seismic isolators was shown in Figure 3.1-4.

Parameters that represent the seismic isolators are listed in Table 3.2-3. The properties in the horizontal direction are determined from the parameters T_2 = 2 sec and β = 0.05, as described in Section 3.1.3.

The stiffness before the lead plug dampers yield, k_1 (see Figure 3.1-4) is set to be 4.0 x k_2, following the guideline JEAG 4614-2000, which says k_1 = (4.0 to 6.5) x k_2 and that the value can be determined by testing actual isolators.

The value of 20 Hz was chosen for the vertical stiffness of the isolators, following the guideline JEAG 4614-2000. This value is verified in Section 3.4.

Rotational stiffness is determined from the vertical stiffness assuming that the isolators are uniformly distributed under the isolated base mat.

3.2.3 Soil-structure Interaction

The standard 4S design is adaptable to a wide variety of supporting soil conditions. The use of seismic base isolation is one of the major reasons for its ability to meet design aims. Because stiffer soil conditions usually yield a larger magnitude response in terms of force or acceleration, a stiffer soil condition, V_s (velocity of shear wave) = 1500 m/sec, is conservatively selected for the representative 4S design. The effect of changes in soil stiffness on response is shown in Section 3.6.

Soil properties and the soil-structure interaction model are listed in Tables 3.2-4 and 3.2-5.

The method of representing soil-structure interaction is based on the theory of dynamic ground compliance.[3.2-2] This method was adopted because it is widely used in Japan to model soil-structure interaction, and because it is the best method for the DAC3N software, which can consider both the nonlinearity of the isolators and soil-structure interaction.

Because the analysis in the vertical direction is linear, a SASSI 2000 finite element ground model is used to represent the soil-structure interaction. The ground model is shown in Figure 3.2-2. A half-space ground model is used because of symmetry.

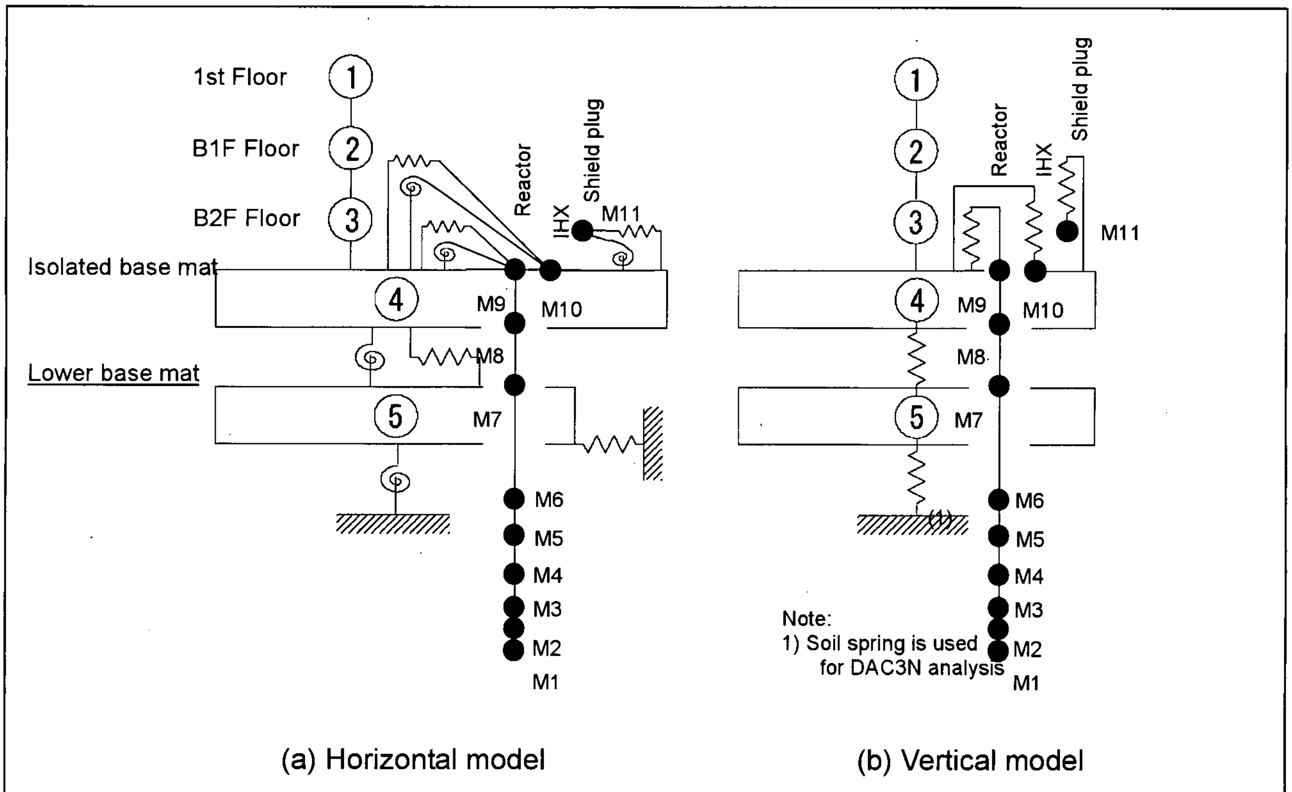


Figure 3.2-1 Dynamic Analysis Models of Reactor Building

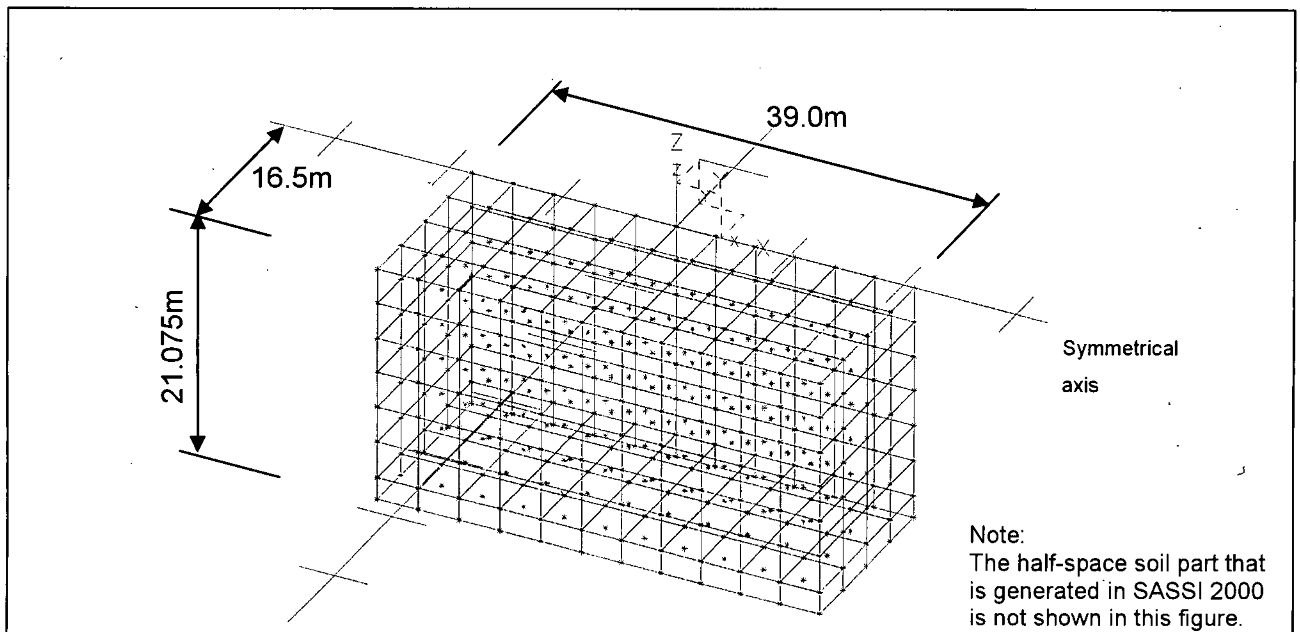


Figure 3.2-2 Dynamic Analysis Model of Soil (for SASSI 2000)

Table 3.2-1
Mass Properties for the Analysis Model (building)

Location		Node No.	Weight (ton)	Mass Moment of Inertia (x10^3 ton-m^2)
Building	1st Floor	1	2,889	152
	B1 Floor	2	2,497	135
	B2 Floor	3	2,854	156
	Isolated base mat	4	5,066	276
	Lower base mat	5	15,475	1,988

Table 3.2-2
Sectional Properties of Beam Elements (building)

Location		Node No. i	Node No. j	Sectional Area (m^2)	Effective Shear Area (m^2)	Geometrical Moment of Inertia (m^4)
Building	B1 Floor	2	1	149	77	6,573
	B2 Floor	3	2	149	77	6,573
	B3 Floor	4	3	149	77	156

Table 3.2-3
Properties of Spring Elements (seismic base isolator)

Node No. i	Node No. j	Stiffness			Damping (%)
		Horizontal (MN/m)[1]	Rotational (GN-m/rad)[5]	Vertical (GN/m)[4]	
3	4	526 (before lead damper yields)[2] 131 (after lead damper yields)[3]	10,951	210	2.0

Notes:

1. Lead damper yields at Q_y = 0.05W (W: weight of isolated building)
2. Stiffness before lead damper yields: $k_1 = 4.0 \mathrm{x} k_2$ (k_2: stiffness after lead damper yields)
3. Corresponding period of vibration is 2 seconds.
4. Corresponding natural frequency of vibration is 20 Hz.
5. Corresponding length of base mat is 25.0m.

Table 3.2-4
Properties of Soil

Velocity of Shear Wave V_s (m/sec)	Modulus of Shear Elasticity g (N/mm^2)	Mass Density	Poisson's Ratio
1,500	5,075	2.3	0.37

Table 3.2-5
Properties of Soil Spring (between soil and lower base mat)

	Horizontal	Rotational	Vertical[1]
Stiffness	487 (GN/m)	149,920 (GN-m/rad)	624 (GN/m)
Viscous damping coefficient	3,523 (MN-sec/m)	2,827 (MN-m-sec/rad)	6,743 (MN-sec/m)

Note:
1. For vertical analysis, a SASSI 2000 soil model is used instead of soil spring elements. Soil spring elements in the vertical direction are used in DAC3N analysis for reference.

3.2.4 References

3.2-1 Lysmer, J., et al., "SASSI 2000 User's Manual, A system for analysis of soil-structure interaction," Rev. 1, University of California, Berkeley, November 1999.

3.2-2 JEAG 4601-1987, "Technical Guideline for Aseismic Design of Nuclear Power Plants," Japan Electric Association, 1987, in Japanese.

3.3 Seismic Design Response Spectra and Time History

The design earthquake for the 4S standard design is an SSE as defined in Regulatory Guide 1.60, scaled with maximum ground acceleration of 0.3g. The Japanese JEAG 4601-2000 guideline states, however, that it is also necessary to pay full attention to the amplitude of the design spectra in the lower-frequency region.

Thus, the 4S design earthquake spectra were determined by modifying the Regulatory Guide 1.60 spectra so that they also cover, in the lower-frequency region, another design earthquake spectrum proposed by the Central Research Institute of Electric Power Industry (CRIEPI) for application of base isolation to nuclear power plants.[3.3-1]

The CRIEPI design spectrum corresponds to the severest design earthquake for base-isolated nuclear power plants.

3.3.1 Design Response Spectra

3.3.1.1 Horizontal Component

Figure 3.3-1 and Table 3.3-1 show the U.S. SSE (0.3g), CRIEPI design, and the 4S design spectra.

In the frequency region lower than 2.5 Hz, the 4S design spectra are larger than the U.S. SSE (0.3g).

In the frequency region higher than 2.5 Hz, the 4S design spectra are the same as the U.S. SSE (0.3g).

3.3.1.2 Vertical Component

Figure 3.3-2 and Table 3.3-2 show the U.S. SSE (0.3g), CRIEPI design, and the 4S design spectra.

In the frequency region lower than 3.5 Hz, the 4S design spectra are larger than the U.S. SSE (0.3g).

In the frequency region higher than 3.5 Hz, the 4S design spectra are the same as the U.S. SSE (0.3g).

3.3.2 Time History of Ground Motion

Time histories of ground motion for dynamic analyses, which match to the design spectra, are created following the rules given by ASCE/SEI Standard 43-05.

As the 4S standard design is not site specific, a random phase is used to create the synthetic time histories.

3.3.2.1 Horizontal Component

The time history of the horizontal component is shown in Figure 3.3-3. Its floor response spectrum is shown in Figure 3.3-4 together with the target design spectrum for comparison.

3.3.2.2 Vertical Component

The time history of the vertical component is shown in Figure 3.3-5. Its floor response spectrum is shown in Figure 3.3-6 together with the target design spectrum for comparison.

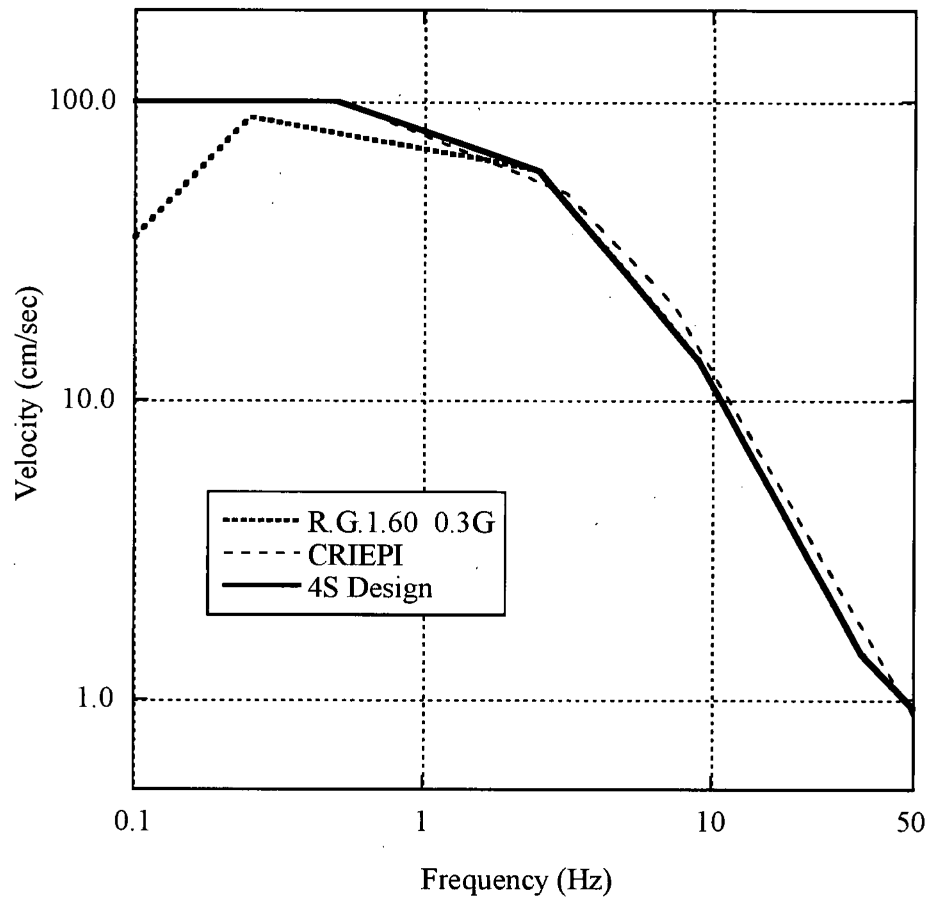


Figure 3.3-1 Seismic Design Spectra (horizontal)

Table 3.3-1
Control Points for Design Spectrum (horizontal)

Design Spectrum	Velocity (cm/sec)								
	0.1 Hz	**0.25 Hz**	**0.5Hz**	**2.5 Hz**	**3.114 Hz**	**7.364 Hz**	**9 Hz**	**33 Hz**	**50 Hz**
Regulatory Guide 1.60 (0.3G)	35.33	88.33		58.62			13.58	1.419	0.936
CRIEPI Proposal	100.0		100.0		49.54	20.81			0.888
4S Design	100.0		100.0	58.62			13.58	1.419	0.936

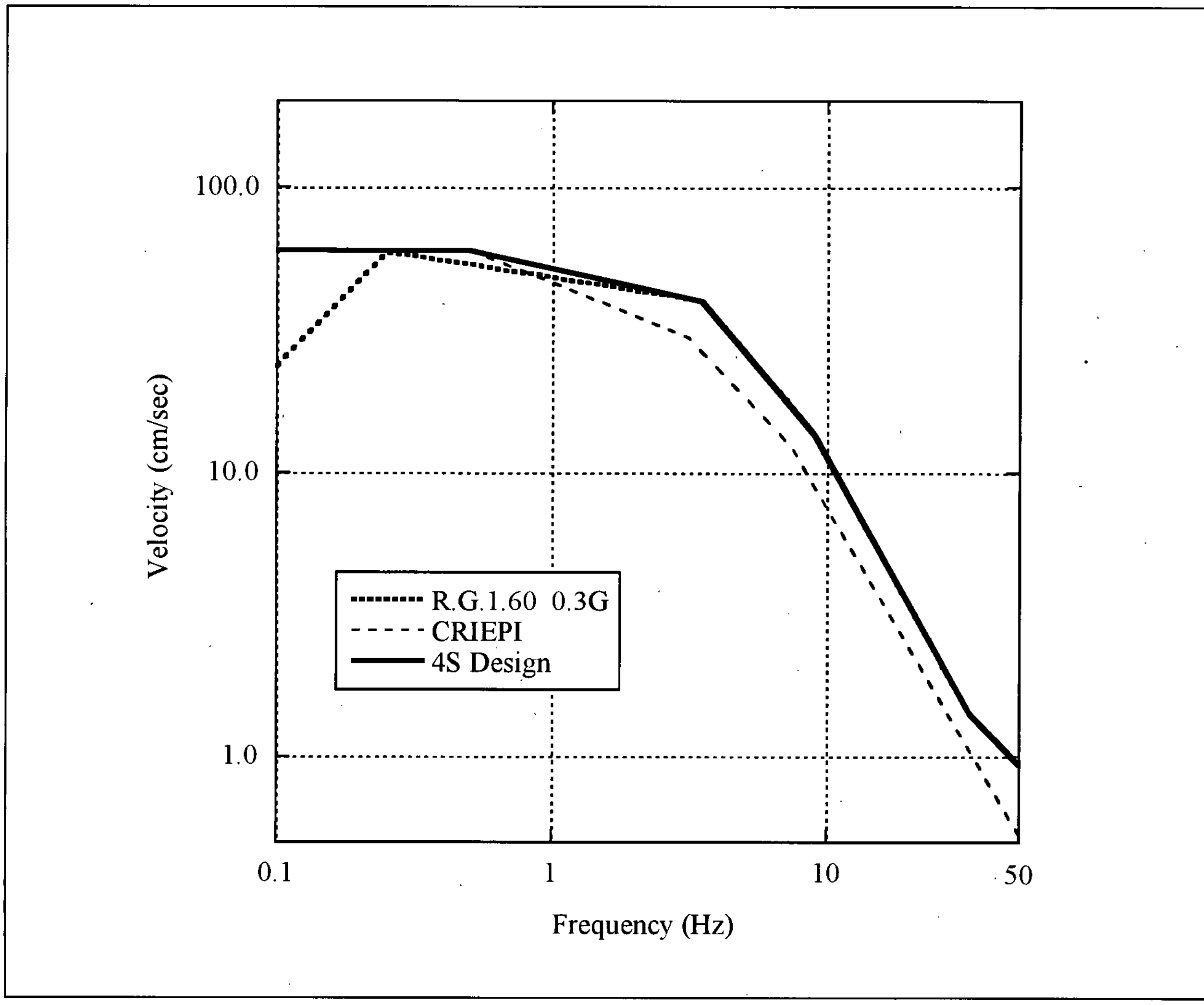


Figure 3.3-2 Seismic Design Spectra (vertical)

Table 3.3-2
Control Points of Design Spectrum (vertical)

Design Spectrum	Velocity (cm/sec)								
	0.1 Hz	0.25 Hz	0.5 Hz	3.114 Hz	3.5 Hz	7.364 Hz	9 Hz	33 Hz	50 Hz
Regulatory Guide 1.60 (0.3g)	23.61	59.03			39.87		13.58	1.419	0.936
CRIEPI Proposal	60.0		60.0	29.72		12.49			0.533
4S Design	60.0		60.0		39.87		13.58	1.419	0.936

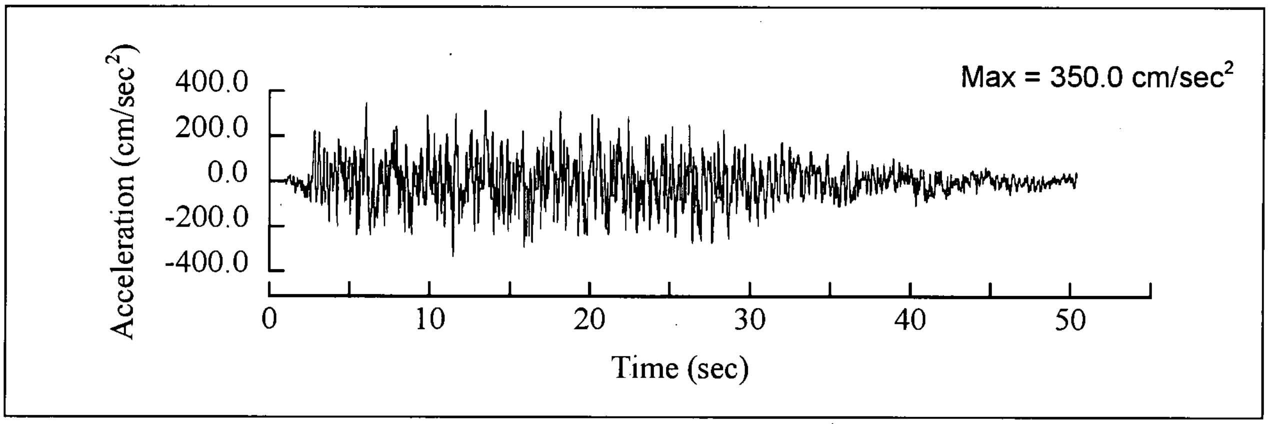


Figure 3.3-3 Time History of Ground Motion (horizontal)

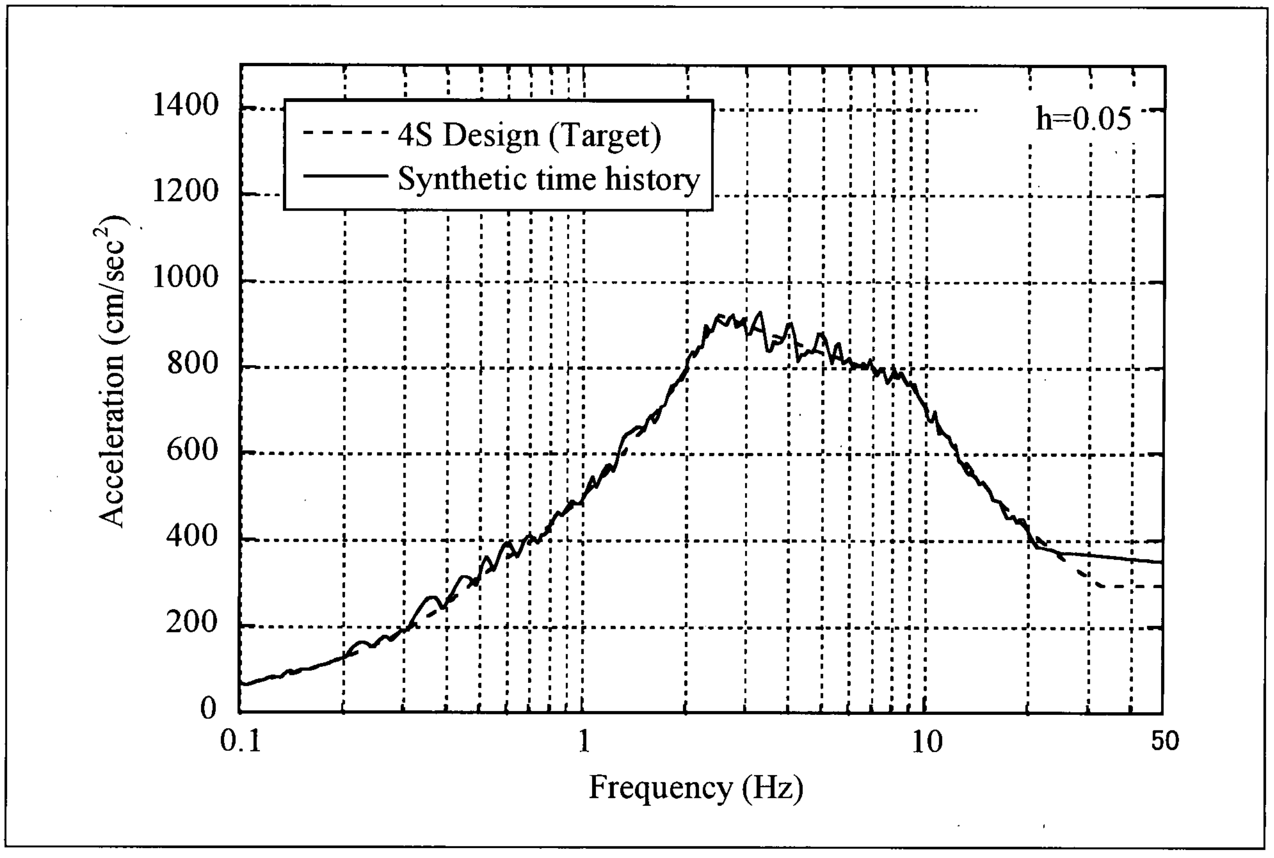


Figure 3.3-4 Floor Response Spectrum of Time History (horizontal)

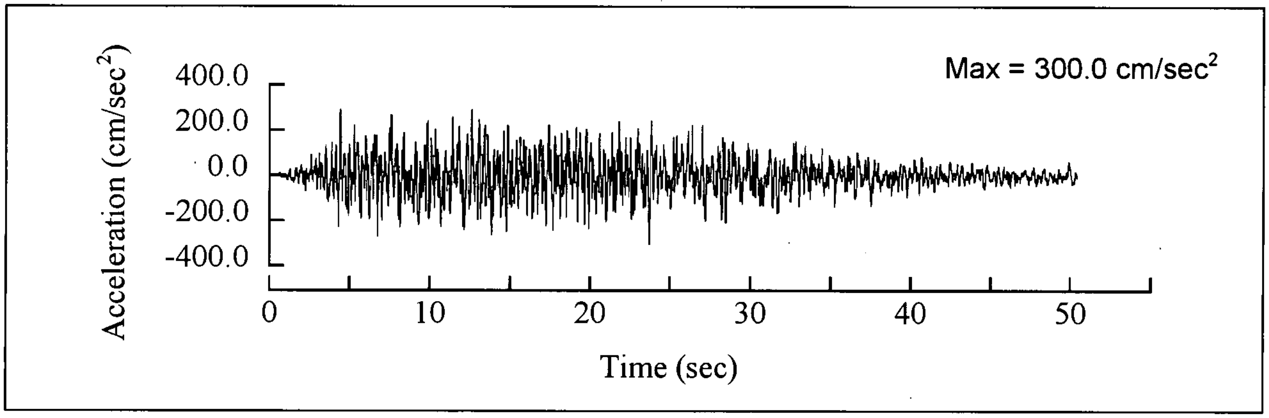


Figure 3.3-5 Time History of Ground Motion (vertical)

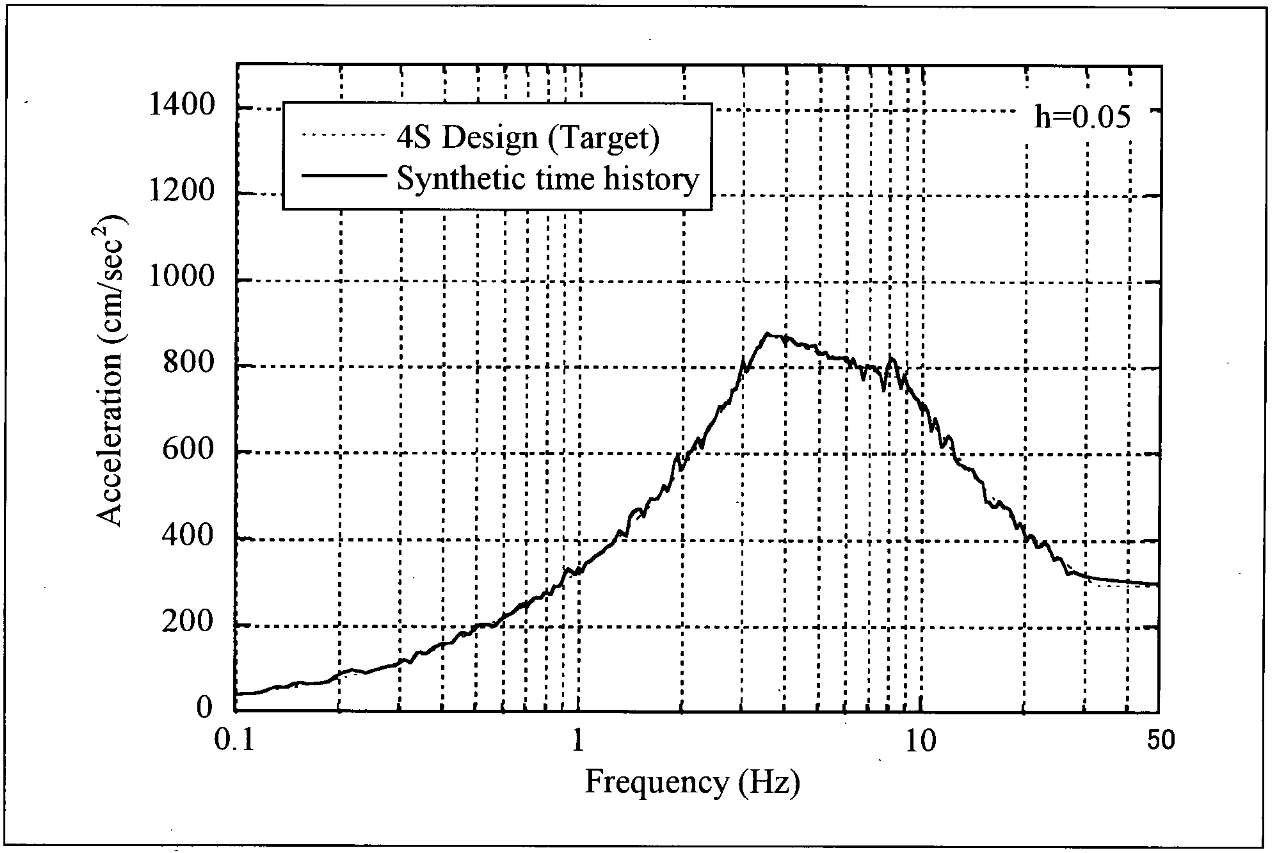


Figure 3.3-6 Floor Response Spectrum of Time History (vertical)

3.3.3 References

3.3-1 Hirata, K., H. Shibata, and T. Fujita, "Method of Ensuring Seismic Safety in the Technical Guidance Proposed for FBR Seismic Isolation System," International Post-SMiRT Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Control of Vibrations of Structures, 1995.

3.4 Results of Dynamic Response Analyses

Dynamic analyses were carried out using the analytical models described in Section 3.2 and the time histories of ground motion described in Section 3.3. The results are discussed in the following sections.

3.4.1 Response in Horizontal Direction

Table 3.4-1 shows the maximum floor responses. The maximum acceleration of the isolated building is 231 to 235 cm/sec^2, which is less than the seismic input 0.3g (294 cm/sec^2). Figure 3.4-1 shows the time history of the floor response at the isolated base mat, and Figure 3.4-2 shows its floor response spectrum together with the target design spectrum for comparison. Figure 3.4-3 shows the peak-broadened floor response spectra of a different damping that will be used for design of equipment on the floor.

Table 3.4-2 shows the maximum floor responses of isolators. The maximum displacement is 212 mm, which will be the design displacement later in the design of the isolators. The base shear ratio, the ratio of *total shear force at isolation level/total weight of isolated building*, is 0.236.

3.4.2 Response in Vertical Direction

Table 3.4-3 shows the maximum floor responses. The maximum acceleration of the isolated base mat is 337 cm/sec^2, which is larger than the seismic input 0.3g (294 cm/sec^2). Figure 3.4-4 shows the time history of floor response at the isolated base mat, and Figure 3.4-5 shows its floor response spectrum together with the target design spectrum for comparison. It can be seen that the peak occurs around 20 Hz (period of 0.05 sec), which is a fundamental natural frequency of the isolators in the vertical direction. Figure 3.4-6 shows the peak-broadened floor response spectra.

Table 3.4-1
Maximum Floor Response (horizontal)

Location		Node No.	Max. Acceleration (cm/sec^2)	Max. Displacement (mm)	Note
Building	1st Floor	1	235	213	
	B1 Floor	2	232	213	
	B2 Floor	3	231	213	
	Isolated base mat	4	232	212	Reactor supporting floor
	Lower base mat	5	356	13	Not isolated

Table 3.4-2
Maximum Response of Isolators (horizontal)

Maximum relative displacement of isolators	212 mm
Maximum base shear ratio(1)	0.236

Note:
1. Ratio of *total shear force at isolation level/total weight of isolated building*

Table 3.4-3
Maximum Floor Response (vertical)

Location		Node No.	Maximum Acceleration (cm/sec^2)	Note
Building	Isolated base mat	4	337	Reactor supporting floor
	Lower base mat	5	279	Not isolated

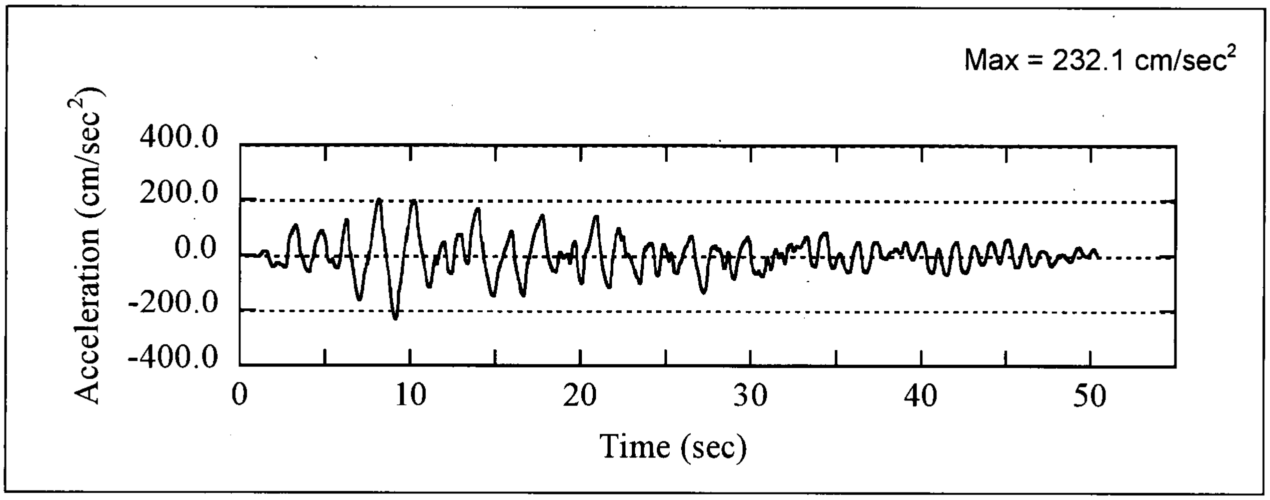


Figure 3.4-1 Acceleration Time History (isolated base mat, horizontal)

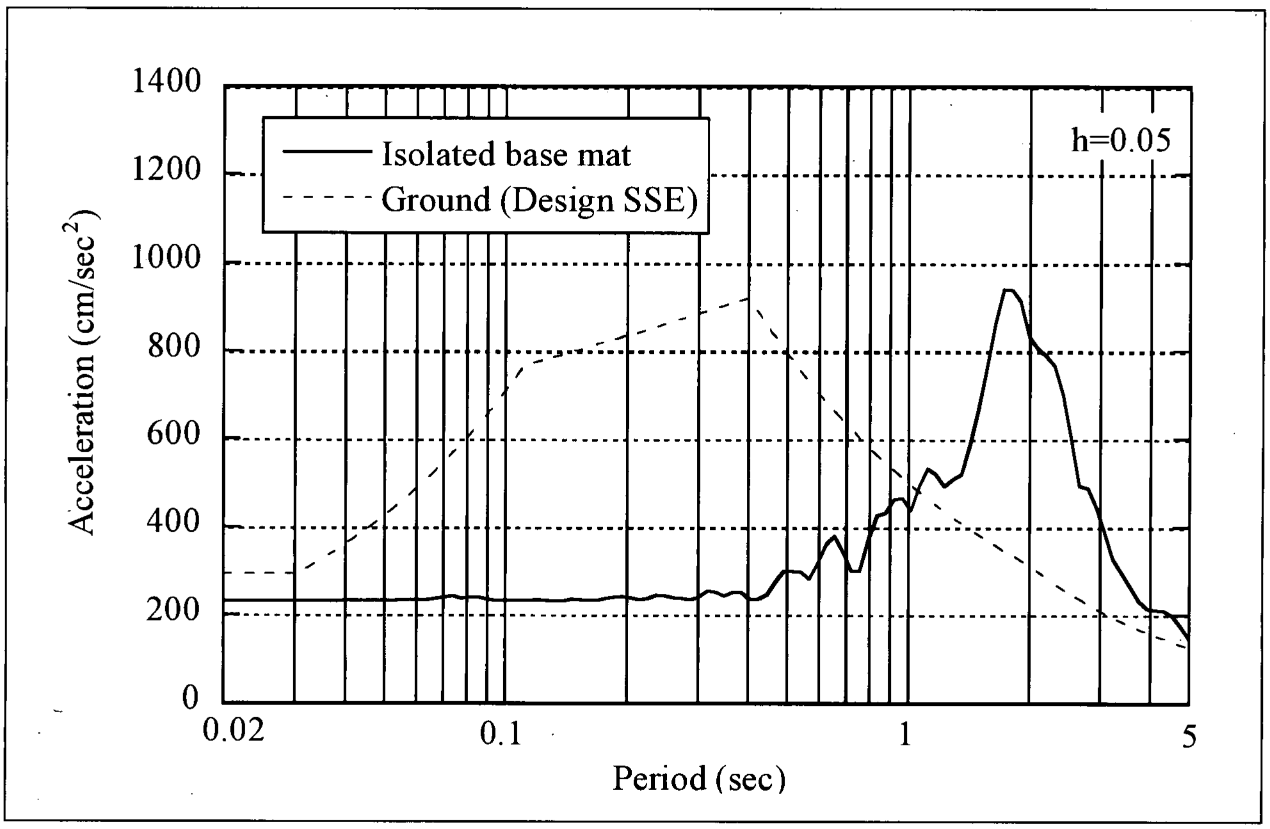


Figure 3.4-2 Floor Response Spectrum (isolated base mat, horizontal)

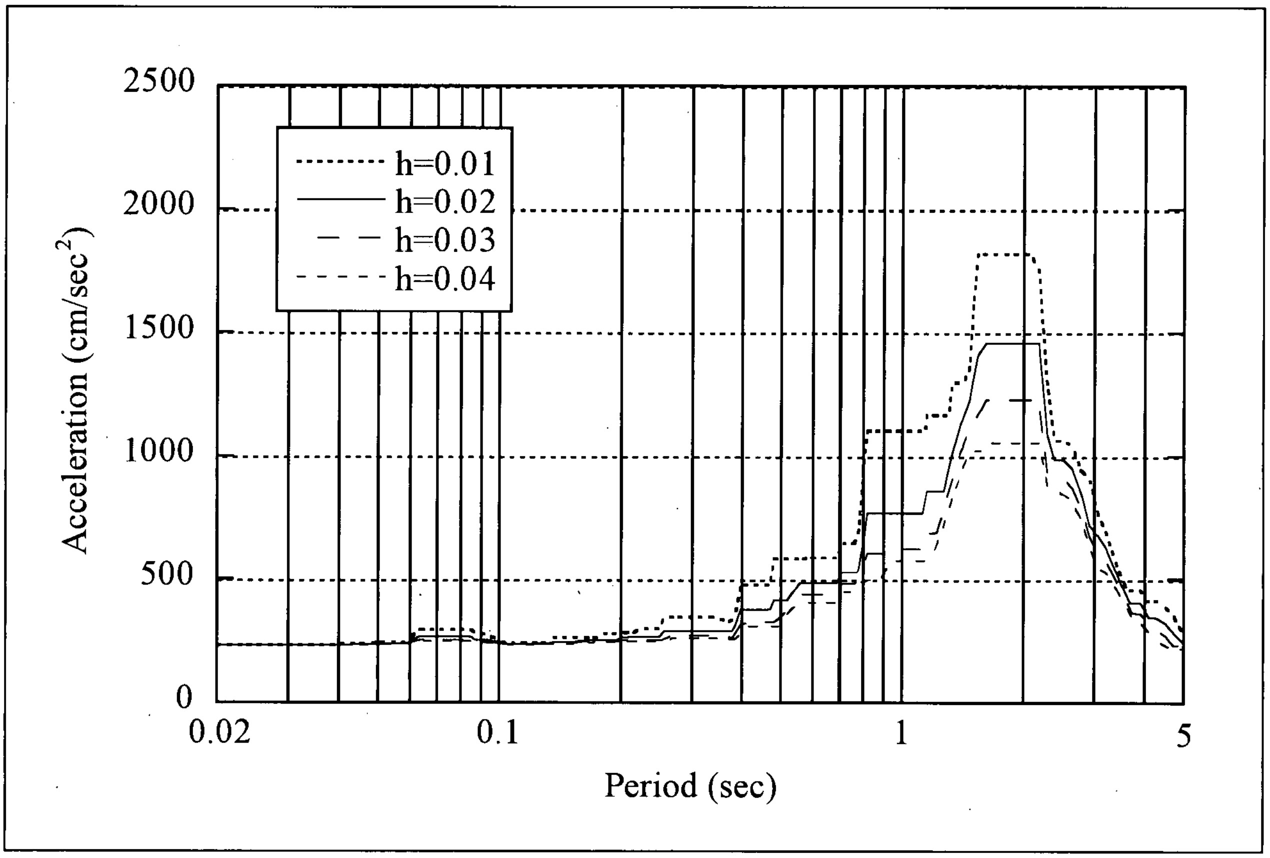


Figure 3.4-3 Peak-broadened Floor Response Spectra (isolated base mat, horizontal)

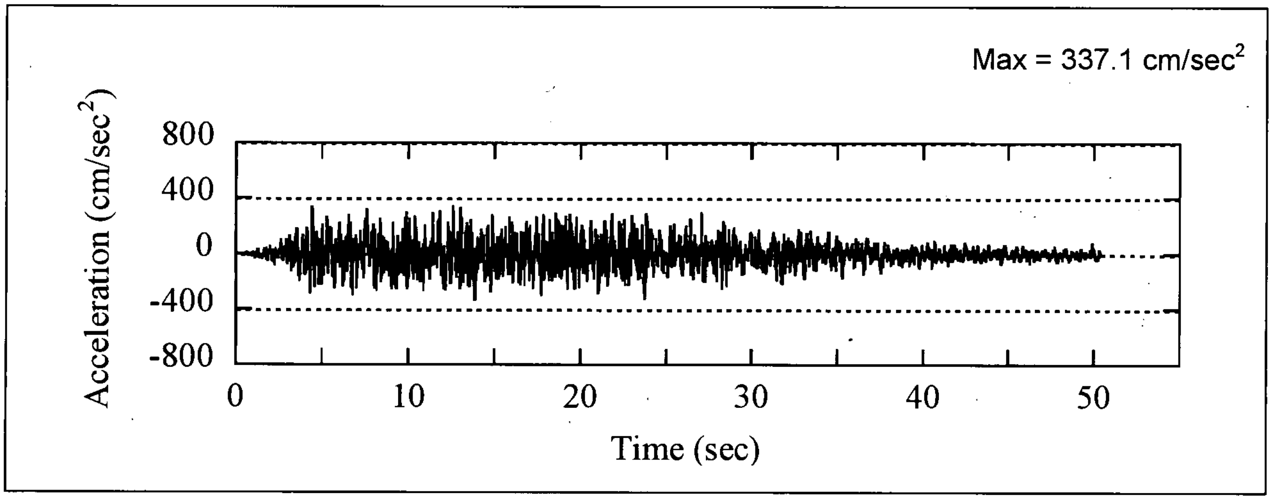


Figure 3.4-4 Acceleration Time History (isolated base mat, vertical)

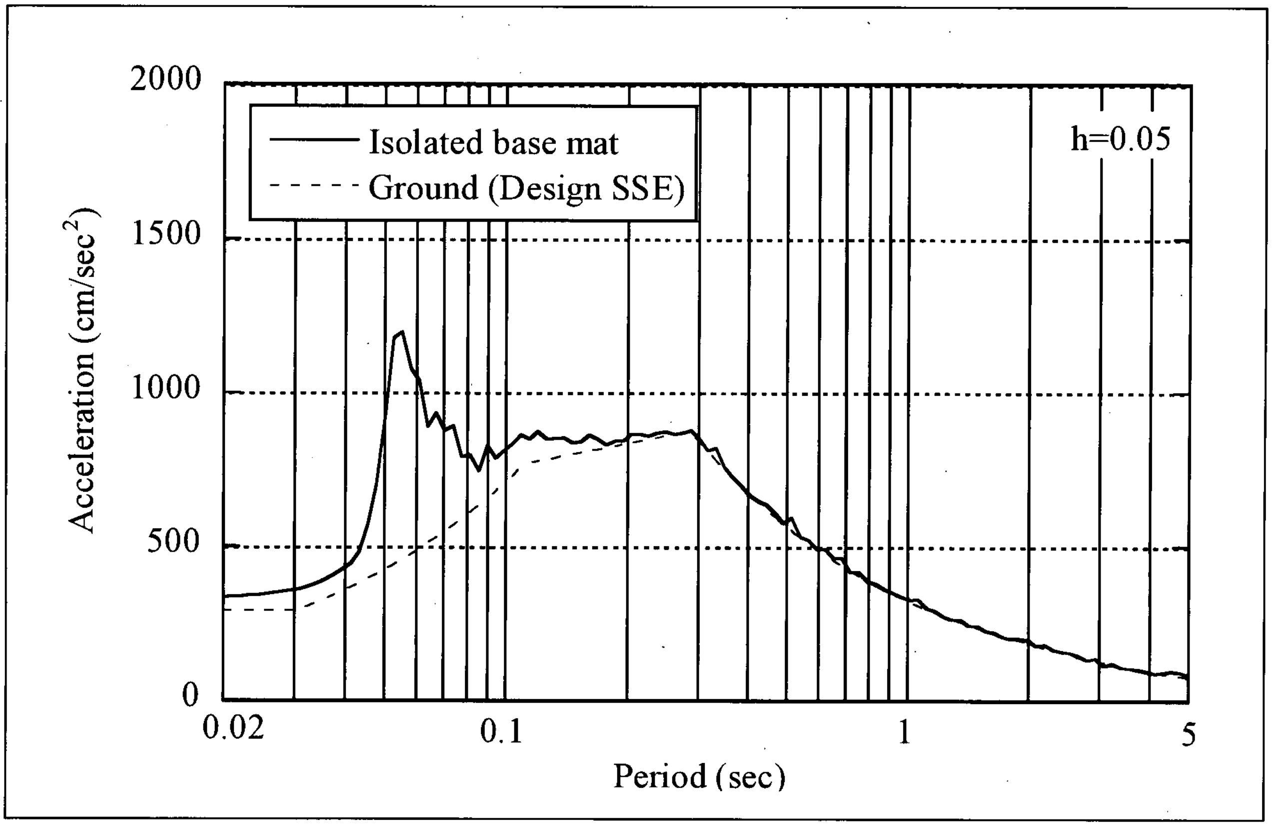


Figure 3.4-5 Floor Response Spectrum (isolated base mat, vertical)

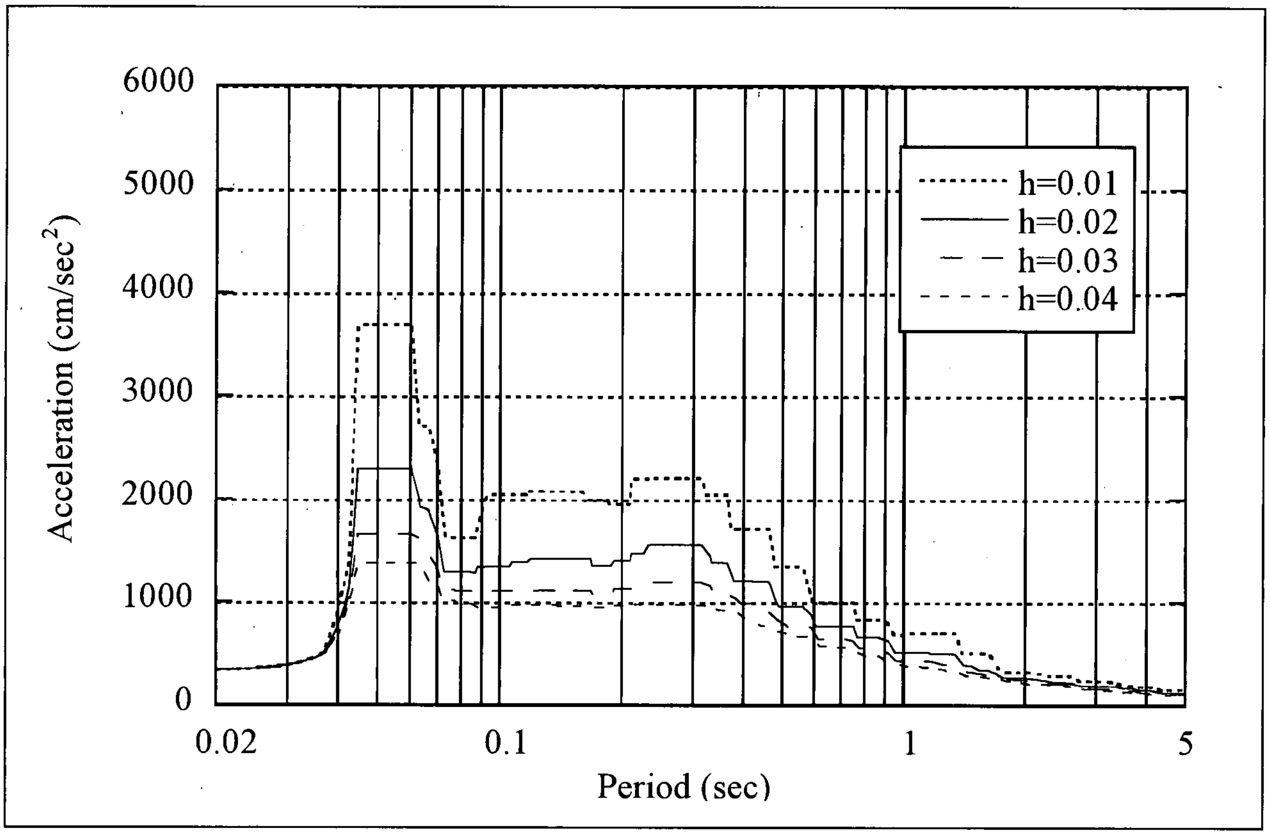


Figure 3.4-6 Peak-broadened Floor Response Spectra (isolated base mat, vertical)

3.5 Design of Isolators

Once the design displacement has been obtained, the necessary properties and specifications of the isolators can be determined. This process for 4S is carried out following JEAG 4614-2000.

3.5.1 Vertical Load Distribution

The calculated vertical load distribution at the level where the isolator devices are located is shown in Table 3.5-1.

3.5.2 Layout of Isolators

The layout and design of the isolators were performed together, because the size of the isolators must be known for layout planning and the size depends on the specific design. As it is known that the maximum diameter of LRBs available on the market is 1600 mm, it was concluded that three 6250 kN pads are required to support the single vertical load of 18,000 kN given in Table 3.5-1.

Figure 3.5-1 shows the layout of the isolators. Table 3.5-2 shows the overall sizes of the isolators, which were determined by the design of isolators described in the next section.

3.5.3 Design Process

JEAG 4614-2000 requires that isolators be designed so that the shear strain of the natural rubber at the design displacement remains within 2/3 of its linear-elastic limit. The linear-elastic limit of natural rubber is regarded as 2.5. These values determine configuration of the natural rubber.

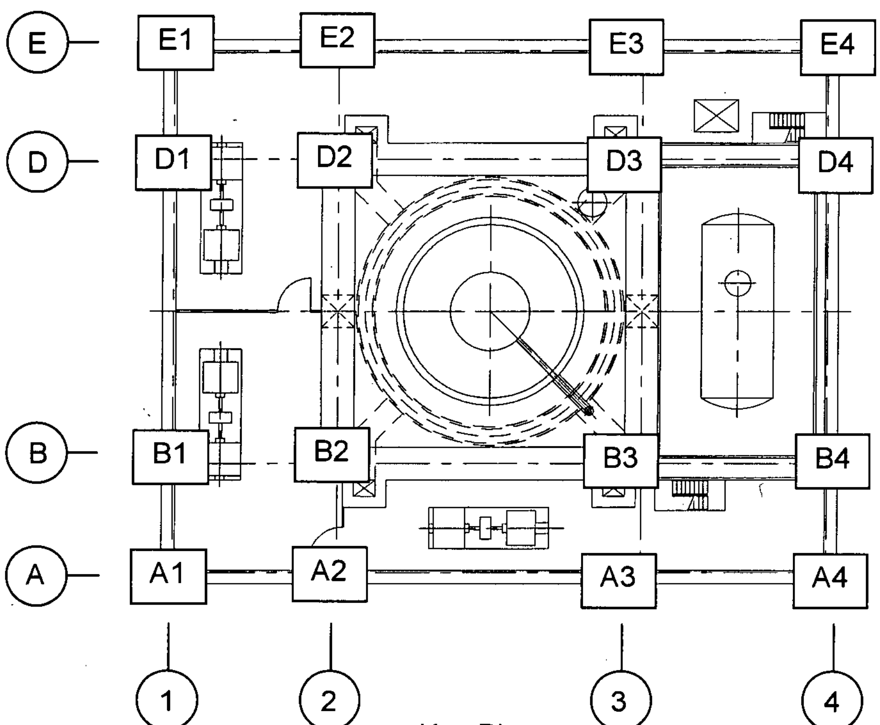
The vertical loads given in Table 3.5-1 and the yield strength of the lead plug damper determine the shape of the lead plug.

These factors determine the configuration of the isolator.

Finally, the dynamic properties such as horizontal and vertical stiffness of the designed isolator are recalculated and checked to determine whether they coincide with initial design requirements. Also, the shape properties such as the proportion of the rubber layer or lead plug are checked to determine whether they meet the requirements.

The isolator design is shown in Table 3.5-3.

Table 3.5-1 Vertical Load Distribution at Isolator Level	
Location	**Vertical Load (kN)**
E1	2,500
E2	6,000
E3	6,500
E4	3,500
D1	5,500
D2	17,000
D3	18,000
D4	7,500
B1 - B4	Same as D1 - D4
A1 - A4	Same as E1 - E4



Key Plan

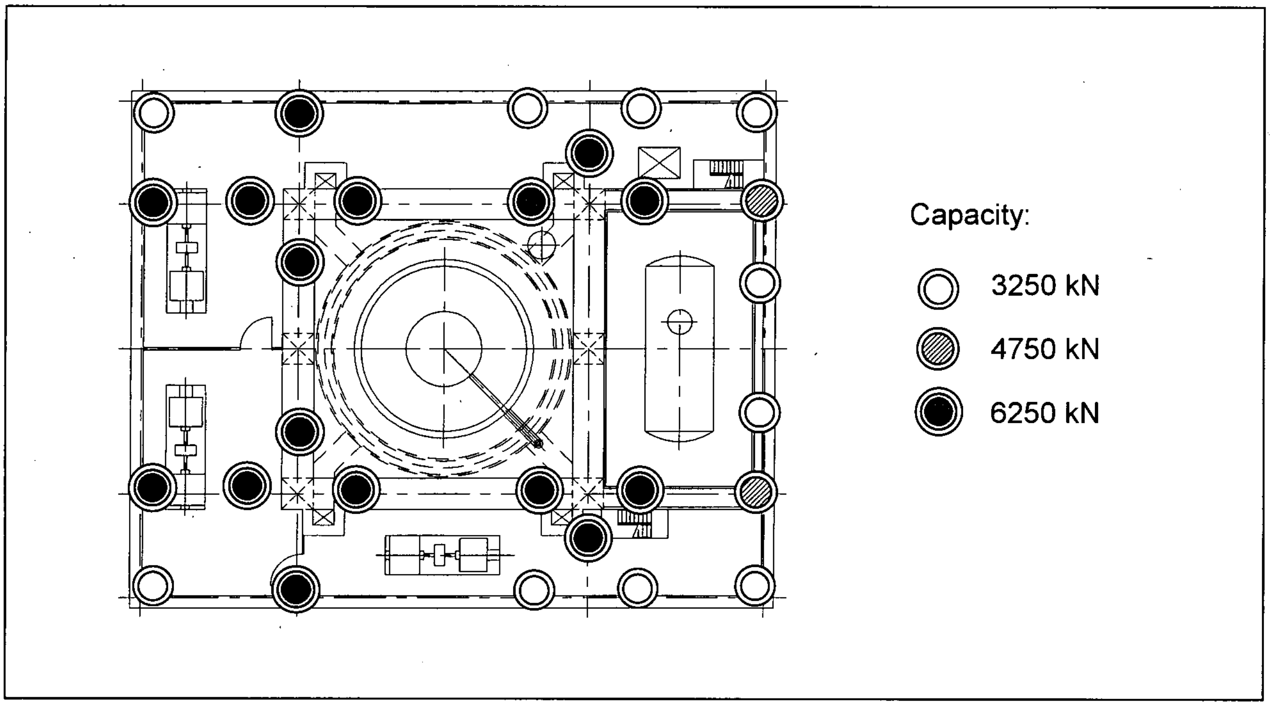


Figure 3.5-1 Layout of Isolators

Table 3.5-2
Designed Configuration of Isolators (overall sizes)

Capacity (kN)	Rubber Diameter (mm)	Device Diameter (mm)	Rubber Layer Height (mm)	Device Height (mm)
3,250	1,050	1,450	220	440
4,750	1,250	1,650	200	420
6,250	1,450	1,850	196	416

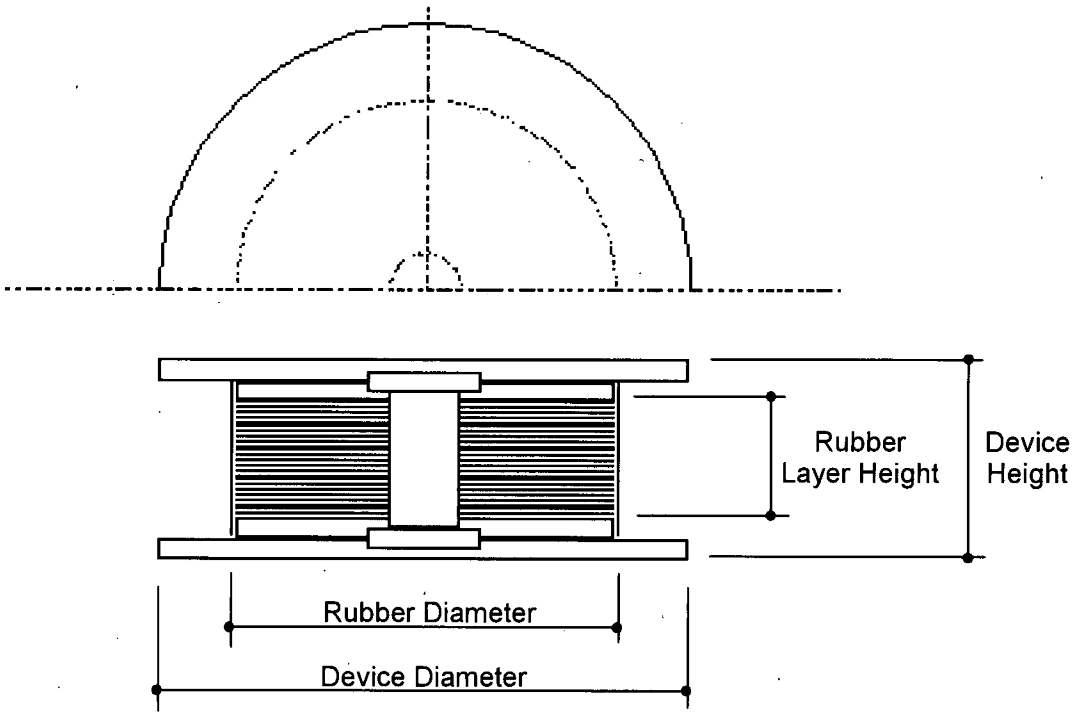


Table 3.5-3
Design Parameters of Isolators

Parameter		Capacity 6,250 kN	4,750 kN	3,250 kN
Design basis	Design earthquake	4S SSE (0.3g)		
	Natural period of vibration (before dampers yield) (sec)	1.0		
	Natural period of vibration (after dampers yield) (sec)	2.0		
	Base shear ratio β when dampers yield	0.05		
	Design displacement (response to SSE) (mm)	212		
	Linear-elastic limit of shear strain of natural rubber	2.5 (250 %)		
Design of an isolator	Displacement at linear-elastic limit (mm)	320	320	320
	Rubber diameter (mm)	1,450	1,250	1,050
	Thickness of one layer of rubber (mm)	11.0	10.0	8.3
	Number of rubber layers	12	13	16
	Total thickness of rubber (mm)	132	130	133
	Thickness of one layer of steel plate (mm)	5.8	5.8	5.8
	Number of steel plates	11	12	15
	Total height of rubber and steel layers (mm)	196	200	220
	Diameter of steel plates (mm)	1,490	1,290	1,090
	Diameter of a lead plug damper (mm)	130	160	132
	Number of lead plug dampers in a device	2	1	1
	Diameter of an end flange plate (mm)	1,850	1,650	1,450
	Thickness of an end flange plate (mm)	60	60	60
Validity check	Linear displacement limit of rubber/design displacement[1]	1.51 (OK)	1.51 (OK)	1.51 (OK)
	Horizontal natural period of vibration (after dampers yield) (sec)[2]	2.03 (OK)	2.04 (OK)	2.03 (OK)
	Vertical natural period of vibration (after dampers yield) (Hz)[2]	20.1 (OK)	19.6 (OK)	19.8 (OK)
	Mean vertical pressure σ (kgf/cm^2)[3]	38.5 (OK)	39.4 (OK)	38.1 (OK)
	Aspect ratio of a lead plug damper (height Hp/diameter Di)[4]	1.66 (OK)	1.37 (OK)	1.82 (OK)
	Shape factor Sf_2[5]	10.98 (OK)	9.62 (OK)	7.91 (OK)
	Shape factor $\sigma / (Sf_1\ Sf_2)$[6]	0.11 (OK)	0.13 (OK)	0.15 (OK)

Notes:
1. Shall be greater than 1.5 (JEAG 4614-2000)
2. Shall be within ±2.0% error from design target
3. Shall be less than 100 kgf/cm^2
4. Shall be between 1.25 and 4.5 (JEAG 4614-2000)
5. Shall be greater than 5
   $Sf_2 = D_R/(n\ t_R)$ (JEAG 4614-2000),
   D_R: diameter of rubber, n: number of rubber layers, t_R: thickness of one rubber layer
6. Shall be less than 0.25 (kgf/cm^2)
   $Sf_1 = A/(\pi\ D_R\ t_R)$,
   A: horizontal cross-section area

3.6 Soil-structure Interaction

The effect of changes in soil stiffness on response is described in this section. Two cases of soil properties, V_s = 1500 m/sec and V_s = 450 m/sec, are compared.

3.6.1 Linearization of Nonlinear Property of Seismic Base Isolation

If DAC3N is used for the analyses, it is possible to accurately evaluate the effect of changes in soil stiffness by modifying the soil parameters given in Table 3.2-5.

SASSI 2000 is widely used in the U.S., however, and is more familiar to many experts in the field. Therefore, the use of SASSI 2000 was preferred in this section to the alternative of demonstrating the accuracy of DAC3N and explaining its theoretical background.

To analyze the model with seismic base isolators using SASSI 2000, the nonlinear properties of the isolators are replaced with equivalent linear properties. The linearization of the nonlinear properties is shown in Figure 3.6-1. Equivalent stiffness is calculated at the maximum design displacement. Equivalent damping corresponds to the energy dissipation due to the hysteresis loop.

The equivalent linear properties of seismic base isolation are shown in Table 3.6-1.

Comparison of the results using SASSI 2000 and DAC3N are presented in Appendix A.

3.6.2 Variation of Soil Properties

The two cases for soil properties are shown in Table 3.6-2.

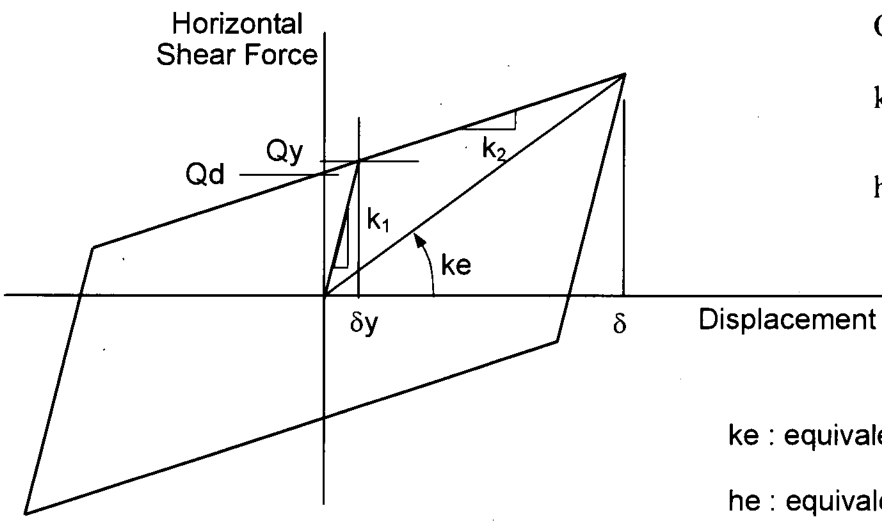
3.6.3 Effect of Soil Properties

Comparisons of floor response spectra at the isolated base mat in the horizontal and vertical directions are shown in Figures 3.6-2 and 3.6-3.

As shown in Figure 3.6-2, the effect of a change in soil properties in the horizontal direction is very small.

On the other hand, as shown in Figure 3.6-3, the effect of a change in soil properties in the vertical direction is obvious. The result of V_s = 1500 m/sec is higher than that of V_s = 450 m/sec.

In consequence, it is clear that the 4S design described in the previous sections was appropriate, as using the soil property of V_s=1500 m/sec corresponds to the more severe condition.



$$Qd = (k_1 - k_2)\cdot \delta y$$

$$ke = k_2 + \frac{Qd}{\delta}$$

$$he = \frac{2Qd\cdot(\delta - \delta y)}{\pi\cdot(k_2\cdot\delta + Qd)}\cdot\frac{1}{\delta}$$

ke : equivalent linear stiffness

he : equivalent damping

Figure 3.6-1 Linearization of Nonlinear Properties of Seismic Base Isolation

Table 3.6-1
Equivalent Linear Properties of Seismic Base Isolation

Equivalent linear stiffness ke	117,100 kN/m
Equivalent damping he (%) + material damping 2%	11.5 %

Table 3.6-2
Properties of Soil

Velocity of Shear Wave V_s (m/sec)	Modulus of Shear Elasticity g (N/mm²)	Mass Density	Poisson's Ratio	Damping (%)
1,500	5,075	2.3	0.37	0.01
450	324	1.6	0.45	0.10

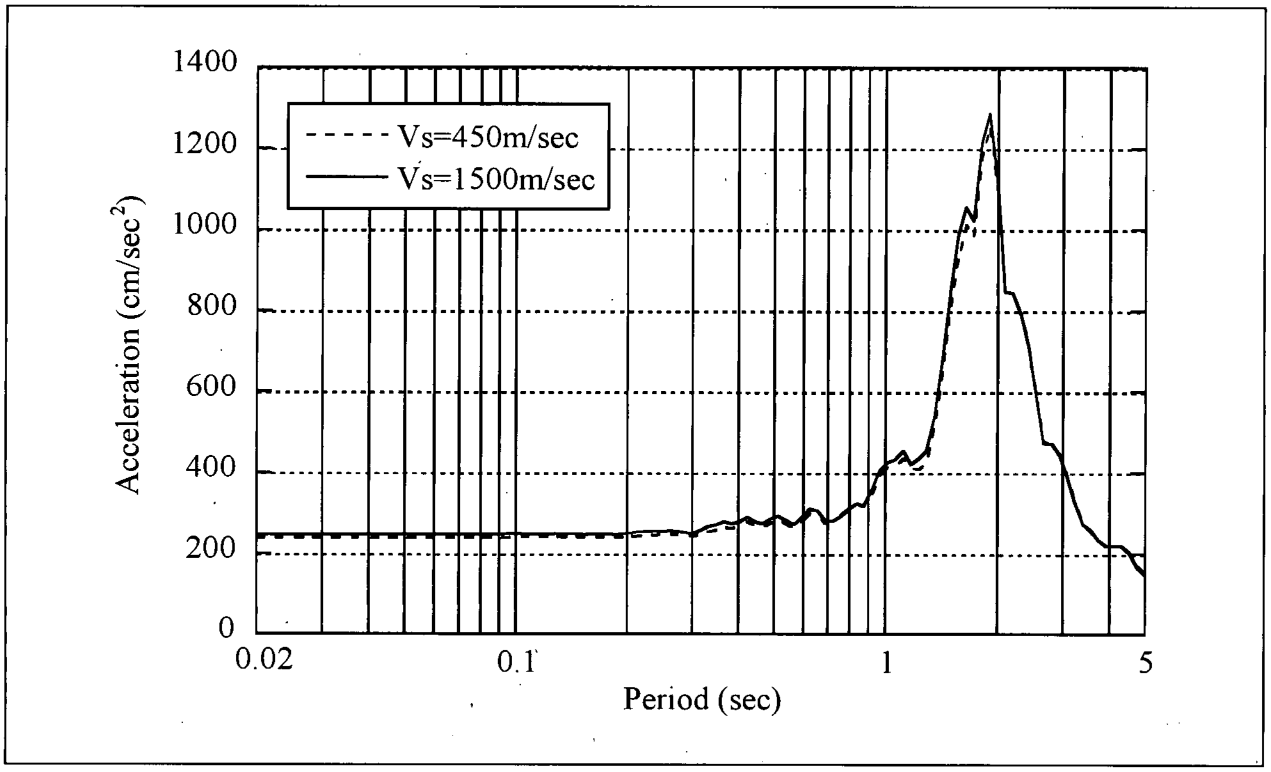


Figure 3.6-2 Floor Response Spectrum (isolated base mat, horizontal)

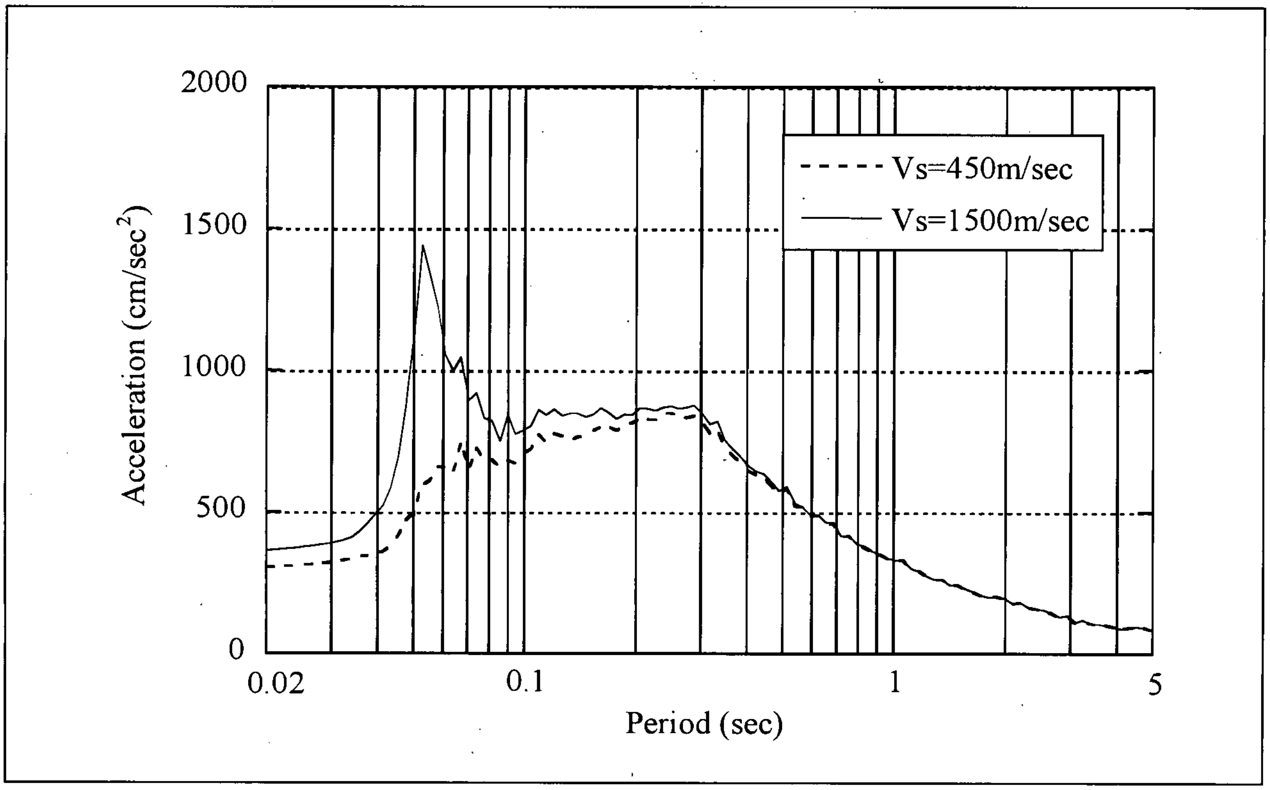


Figure 3.6-3 Floor Response Spectrum (isolated base mat, vertical)

3.7 Safety Margin

3.7.1 Design Displacement of Isolators

According to JEAG 4614-2000, the maximum displacement due to the design earthquake shall be less than 2/3 of the linear-elastic limit of rubber. This linear limit is not the yielding of the lead plug damper as shown in Figure 3.1-4, but the linear limit of rubber as shown in Figure 3.7-1. Beyond the linear limit of rubber, moderate hardening occurs until the rubber ruptures. As the strain that corresponds to the linear limit is around 2.5, and the strain at rupture corresponds to around 4.5, the linear limit of rubber is around 1/1.8 (2.5/4.5) of the rupture strength.

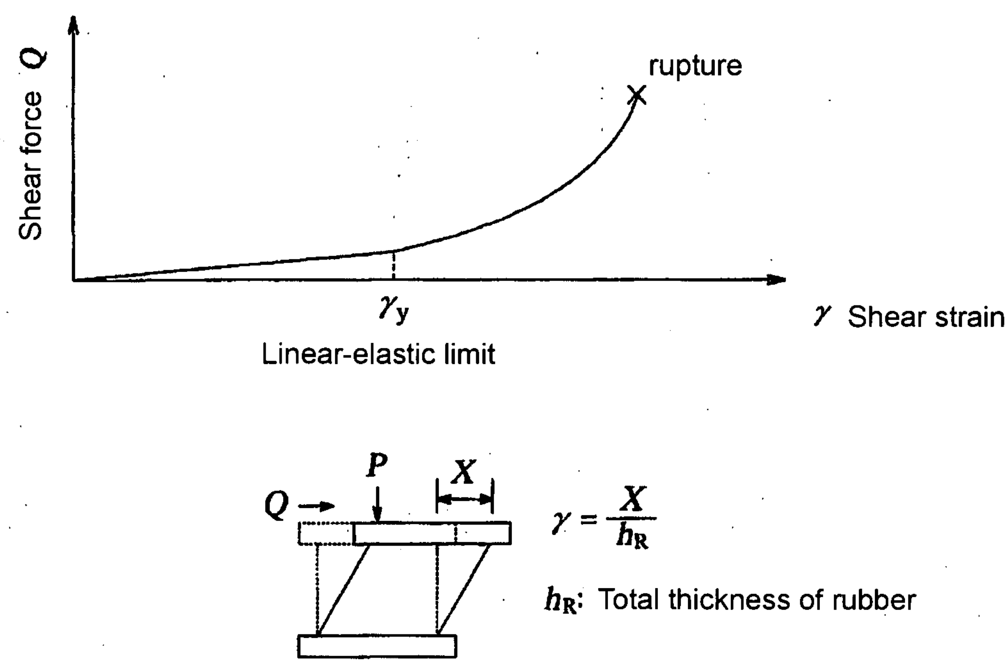
Therefore, the design displacement is 0.67 (2/3) of the linear limit, and 0.37 (2/3 x 1/1.8) of the rupture strength.

Table 3.7-1 shows displacement at base isolation when the input earthquake is 0.3g and higher. The case 0.45g is selected because ASCE 7-05 Chapter 17 requires consideration not only of a design earthquake but also a maximum considered earthquake (MCE), which is 3/2 of the design earthquake. Displacements of up to 0.5g input are all less than the rupture displacement, which is 576 mm (designed linear limit 320 mm x 1.8).

3.7.2 Size of the Seismic Gap

A seismic gap of sufficient size between the isolated portion and the nonisolated portion of the structures shall be provided. JEAG 4614-2000 requires that the size be greater than the linear limit displacement, which is 3/2 of the design displacement. ASCE 7-05 Chapter 17 requires that the size be greater than the total maximum displacement, which is the displacement due to the MCE.

A seismic gap of 500 mm was determined for the 4S standard design. This size meets the requirements of both JEAG and ASCE with an additional margin, regarding 3/2 x SSE (0.45g) as the MCE level for nuclear power plants.



JEAG 4614-2000

Figure 3.7-1 Shear-strain Relation of a Seismic Base Isolator

Table 3.7-1
Horizontal Displacement and Designed Size of Seismic Gap

Displacement	0.3g input	212 mm
	0.45g input	365 mm(1)
	0.5g input	415 mm(1)
Designed size of seismic gap		500 mm

Note:
1. Displacement is greater than the designed linear-elastic limit of 320 mm. The hardening effect of rubber beyond the linear limit is not included in the analysis, so the result is conservative.

4 FIRE PROTECTION

Fire protection for the isolation system shall meet that required for the building columns, walls, or other structural elements in which it is installed, per ASCE 7-05.

This means that, in some cases, isolators need not be fire-protected; for example, when the isolators are installed in a separate space that is not occupied and that does not contain flammable or combustible materials. The same requirement applies to Japanese isolators.

Therefore, based on their location in the unoccupied space between the isolated base mat of the reactor building and the lower base mat, the 4S isolators need no fire protection.

5 MAINTENANCE OF BASE ISOLATORS

5.1 Inspection

Seismically isolated buildings shall have a periodic monitoring, inspection, and maintenance program for the isolation system established by the engineer responsible for the design of the system per ASCE 7-05. The objective of such a system shall be to ensure that all elements of the isolation system can perform to minimum design levels at all times.

A similar inspection program is also required by JEAG 4614-2000.

Spare isolators will be kept in the isolation basement under load to represent the service condition on the isolators. This will allow periodic testing to assess the long-term aging characteristics of the isolators.

Among the possible causes of aging, the effects of environmental temperature and radiation on the characteristics of the isolators are briefly described in Appendix B.

5.2 Provisions for Replacement of Isolators

Although the durability of the isolators is sufficiently high, and the need for replacement is not expected in the plant design lifetime, appropriate space around the isolators is provided in the design to allow for jacking and removal and replacement of the isolators.

6 ADVANTAGES OF SEISMIC BASE ISOLATION

The fundamental natural frequencies of the reactor and the other equipment are higher than 1.0 Hz. As shown in Figure 3.4-2, the acceleration response in this frequency region is quite low, which makes design of the reactor and equipment simple. This is one reason why 4S adopts base isolation.

Another reason is, as shown in Figure 3.6-2, that the response of structures above the isolation is less dependent on site conditions. This allows the 4S design to be standardized and universal.

Also, from the viewpoint of construction, base isolation enables modularized construction that requires the least onsite work.

7 LICENSING IN THE U.S.

7.1 SSE Evaluation

The safe shutdown earthquake considered in the present 4S standard design is a design earthquake spectrum that is a combination of spectra defined by Regulatory Guide 1.60 and Japanese design spectra proposed by CRIEPI.

As Japanese design spectra are different from those for the U.S. SSE, an adequate SSE shall be evaluated for a site-specific design. This will be achieved by following Regulatory Guide 1.208.

7.2 Base Isolation Design

Because there is no design code for the application of base isolation to nuclear power plants in the U.S., it is expected that submittal of a topical report in the site-specific design will fill the gap between the safety requirements for a nuclear power plant and ASCE 7-05.

As for the specific design guideline to be used to design the shape of the isolators, JEAG 4614-2000 may be used in the site-specific design. However, use of the JEAG guideline will not be a decisive factor, because the product testing required by ASCE 7-05 will verify the design.

7.3 Testing Isolators

ASCE 7-05 requires two phases of testing; prototype and production. In the code, a detailed description of an extensive series of tests is given for the prototype tests. Generally, at least two isolators of each type and size for a project must be prototype tested.

This prototype testing will be done in the process of site-specific design.

It is expected that, in the process of obtaining NRC approval for isolation devices for the 4S, dynamic, bidirectional loading tests, and extreme loading limit-state tests will be required to demonstrate satisfactory performance of the devices under actual design loading conditions.

APPENDIX A
COMPARISON OF RESULTS OF SASSI 2000 AND DAC3N

Floor response spectra of the isolated base mat in the horizontal direction are compared in Figure A-1. The software applications used in the analyses, SASSI 2000 and DAC3N, were introduced in Section 3.2, and the equivalent linearization scheme of the nonlinear seismic base isolation property was described in Section 3.6.

The equivalent linear results of SASSI 2000 and DAC3N are almost identical.

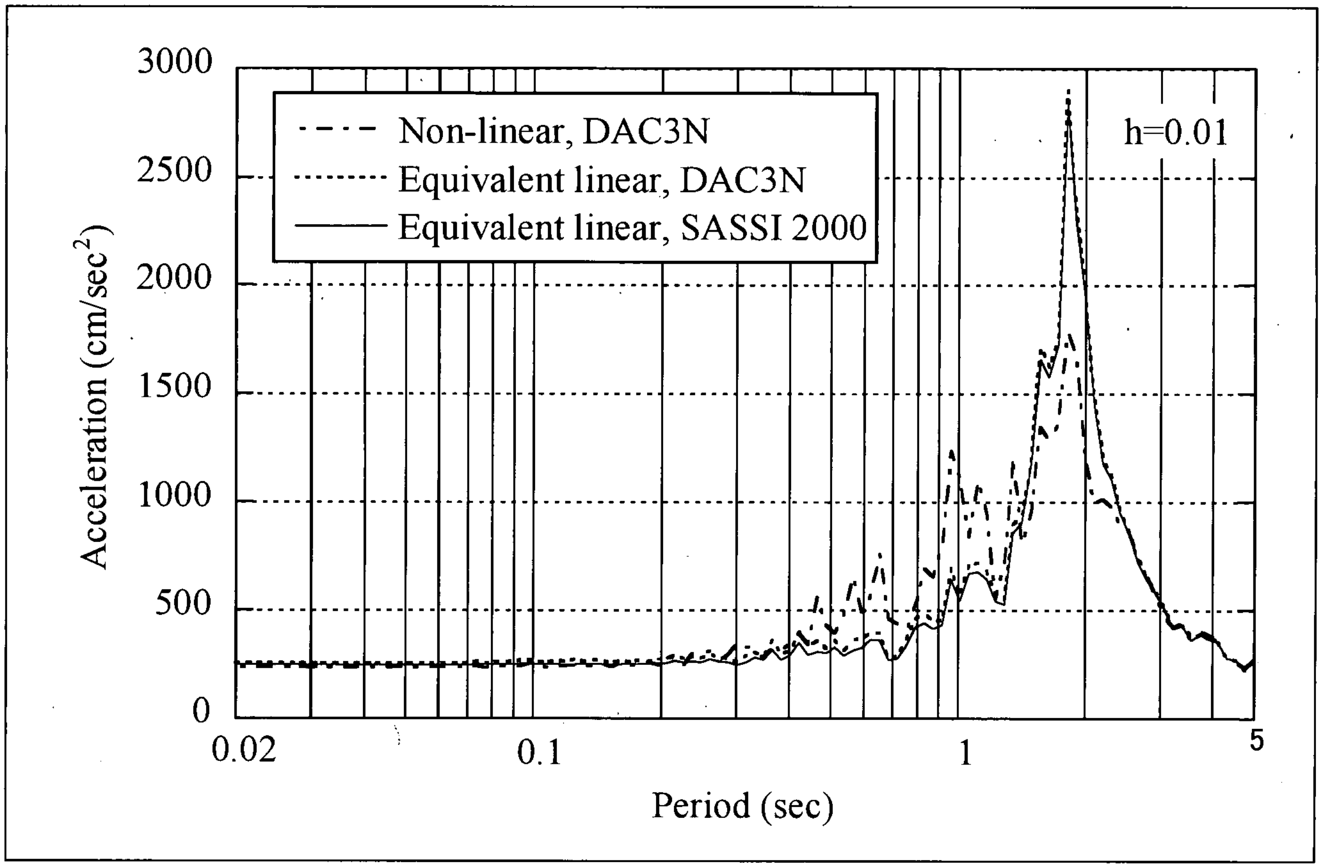


Figure A-1 Floor Response Spectra of Isolated Base Mat in Horizontal Direction

APPENDIX B
EFFECT OF TEMPERATURE AND RADIATION ON ISOLATORS

B.1 Effect of Temperature

In general, natural rubber becomes brittle at approximately -25°C, and remains elastic when the temperature is not lower than -20°C. The effects of temperature on characteristics of rubber in isolators were reported by Hirata et al.[B-1] Figure B-1 shows the results. This figure shows that the characteristic change in elasticity of rubber used for the isolators remains steady when the temperature is not lower than -20°C. Since the isolators in the 4S design are located under the reactor building and far below grade, this temperature limit will not be a concern.

B.2 Effect of γ-ray Radiation

The effect of γ-ray radiation on natural rubber and high-damping rubber was reported by Hirata et al.[B-1] Figure B-2 shows the results for natural rubber, which is used for LRB isolators. It was shown that the characteristics of the rubber remain normal when the accumulated γ-ray dose is less than 10^6 R (roentgen). That means the isolators retain normal performance characteristics if they are located outside the bioshield wall, as they are in the 4S design.

B.3 References

B-1 Hirata, K., S. Yahana, et al., "Study on Design Method for Seismically Isolated FBR Plants," Central Research Institute of Electric Power Industry, Abiko Research Laboratory Rep. No. U34, Dec. 1998, in Japanese.

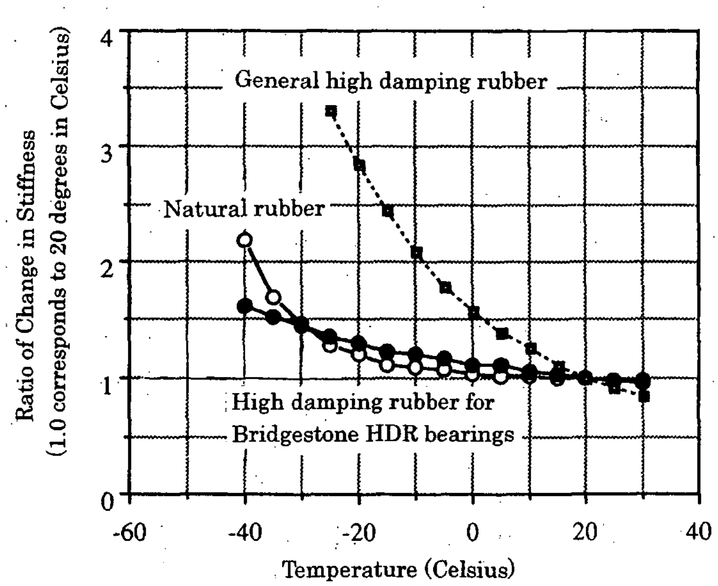


Figure B-1 Effect of Temperature Change on Stiffness of Rubber(B-1)

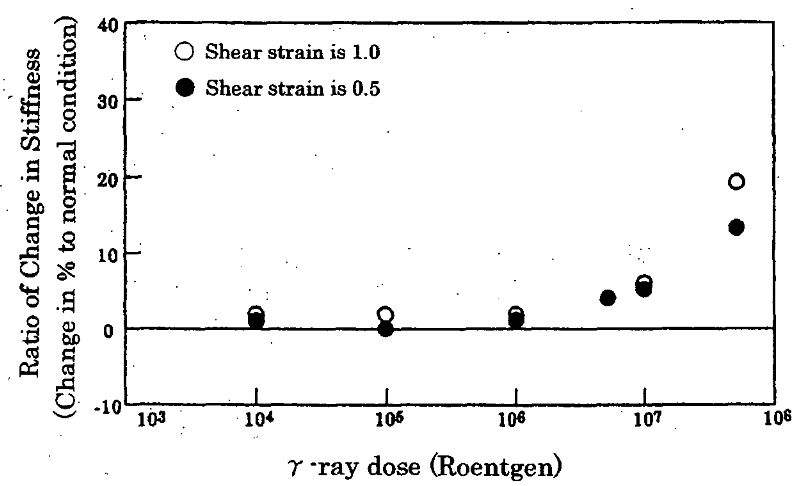


Figure B-2 Effect of γ-ray Dose on Stiffness of Rubber(B-1)